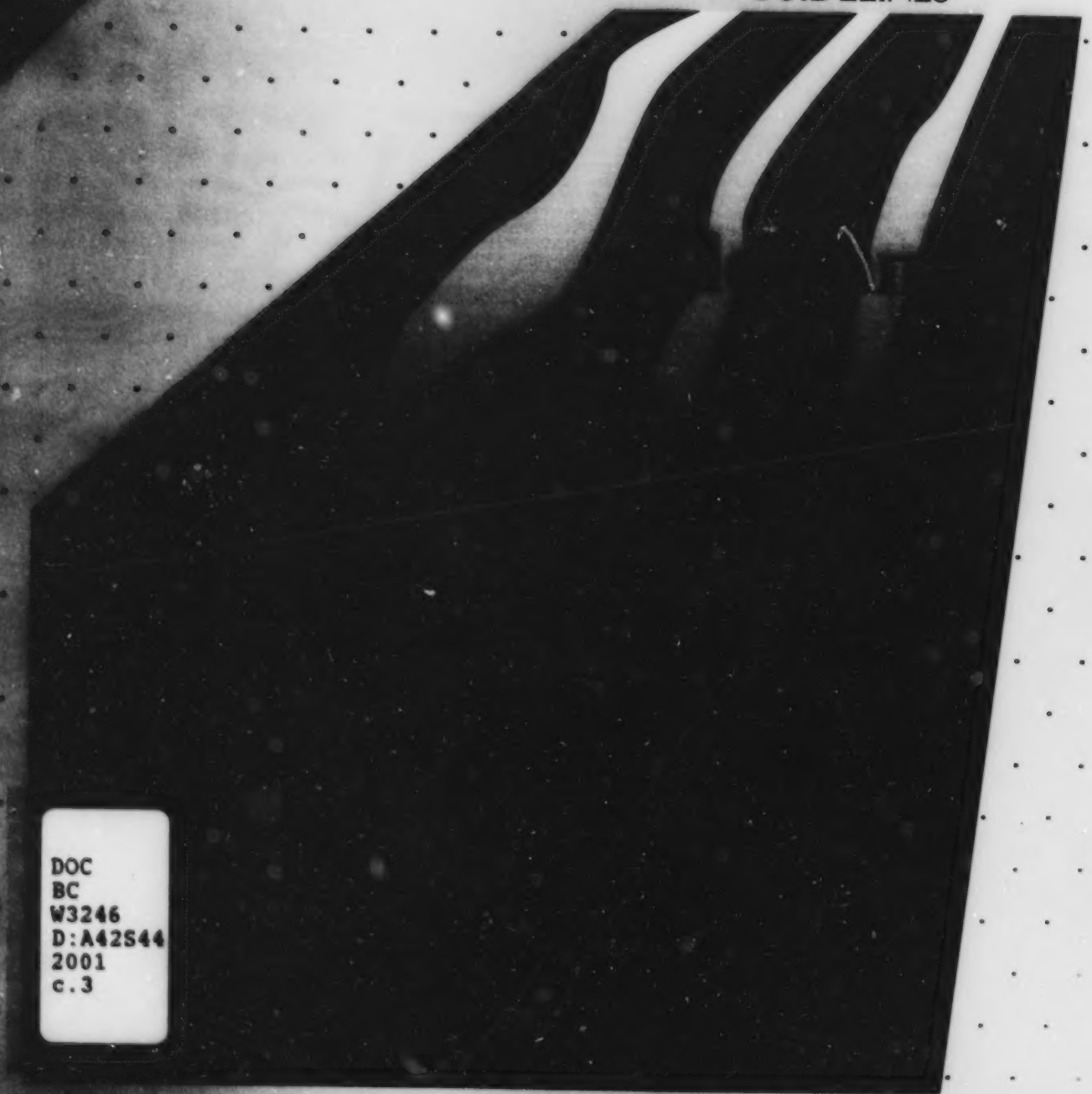
Ministry of Water, Land and Air Protection

OVERVIEW — SELENIUM

water is our vital resource

Water Quality

GUIDELINES



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WATER PROTECTION BRANCH
MINISTRY OF WATER, LAND AND AIR PROTECTION

Ambient Water Quality Guidelines for Selenium

OVERVIEW

Prepared pursuant to Section 2(e) of the
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SUMMARY

THIS DOCUMENT is one in a series that establishes ambient water quality guidelines (Table 1). This document is mainly based on a report originally prepared by the British Columbia Ministry of Water, Land and Air Protection in 1997 and then updated in year 2001. It sets guidelines for selenium (Se) to protect drinking water, freshwater and marine aquatic life, and agricultural water uses.

Table 1: Recommended guidelines for Selenium

Water use	Guideline (Total Se)
Drinking water	10 µg/L*
Aquatic Life	
Freshwater	2 µg/L**
Marine	2 µg/L**
Sediment#+	2 µg/g dw**
Tissue+	1 µg/g ww/bw**
Marine Life	2 µg/L**
Wildlife	4 µg/L**
Irrigation	10 µg/L**
Livestock Watering	30 µg/L**

* Maximum concentration

** Average concentration – based on at least 5 weekly samples taken over a 30-day period in water column or 5 independent sediment and tissue samples.

\+ These are interim guidelines and apply to both freshwater and marine environments.

\# Total organic carbon assumed to be 5%.

Guidelines were not set for recreational and industrial water uses, since relevant Se toxicity data for these uses were not available in the literature.

Selenium can be both beneficial as well as toxic to biota. In aquatic environments, organisms accumulate Se from both water and food. The bioaccumulation of Se through the diet, however, is usually greater than the direct uptake from water. Therefore, toxic effects of selenium in food may be more significant than the waterborne Se.

PREFACE

THE MINISTRY OF WATER, LAND AND AIR PROTECTION develops ambient water quality guidelines for British Columbia. This work has two goals:

- to provide guidance for the evaluation of data on water, sediment and biota, and
- to provide basis for setting site-specific ambient water quality objectives.

The guidelines represent safe conditions or safe levels of a substance in water. Guideline is defined as "a maximum and/or a minimum value for a physical, chemical or biological characteristic of water, sediment or biota, which should not be exceeded to prevent detrimental effects from occurring to a water use under given environmental conditions."

The guidelines are applied province-wide, but they are use-specific, and are being developed for these water uses:

- raw drinking water, public water supply and food processing[1]
- aquatic life and wildlife
- agriculture (livestock watering and irrigation)
- recreation and aesthetics [2]
- industrial water supplies

[1] The guidelines apply to an ambient raw water source before it is diverted or treated for domestic use. The Ministry of Health Services regulates the quality of water for domestic use after it is treated and delivered by a water purveyor.

[2] Guidelines relating to public health at bathing beaches will be the same as those developed by the Ministry of Health Services, which regulates the recreation and aesthetic water use.

The guidelines are established after considering the scientific literature, existing guidelines from other jurisdictions, and environmental conditions in British Columbia. The scientific literature provides information about the effects of toxicants on various life forms. This information is not always conclusive because it is usually based on laboratory work that, at best, only approximates field conditions. To compensate for this uncertainty, and applying the "precautionary principle", the guidelines have built-in safety factors that are conservative, but reflect the natural background levels.

The guidelines are used to set ambient site-specific water quality objectives for waterbodies. In setting the objectives, considerations are given to present and future water uses, waste discharges, hydrology, limnology, oceanography, and existing background water quality.

In most cases, the objectives are the same as the guidelines. However, when natural background levels exceed the guidelines, the objectives could be less stringent than the guidelines. In rare instances—for example, if the resource is unusually valuable or of special provincial significance—the safety factor could be increased, enabling objectives to be more stringent than the guidelines. Another approach would be to develop site-specific objectives by conducting toxicity experiments in the field. However, because this approach is costly and time consuming, it is seldom used.

Neither the guidelines nor the objectives derived from them have any legal standing. However, objectives can be used to calculate waste discharge limits for contaminants. These limits are outlined in waste management permits, orders and approvals, all of which have legal standing. Objectives are not usually incorporated as conditions of a permit.

Water quality guidelines are subject to review and revision, as new information becomes available or as other circumstances dictate.

INTRODUCTION

SELENIUM IS AN ESSENTIAL TRACE ELEMENT for animal nutrition. It can also be toxic to plants, animals and humans at higher concentrations. The severity of selenium effects in food and water depends on the amount ingested and the length of exposure. A number of systemic effects including respiratory, cardiovascular, gastrointestinal, haematological, musculoskeletal, renal, dermal, endocrine, and changes in body weight have been reported in humans and animals exposed to selenium. However, little is known about the specific mechanisms by which Se and its compounds exert their toxicity. Selenium can replace sulphur in biomolecules, especially when the selenium concentration is high and the sulphur concentration is low in the organism. Skin, hair, and nail damage are among the significant indicators of chronic selenium exposure.

Selenium poisoning in animals has been reported in areas of high Se concentration in soils (e.g., seleniferous soils). Clinical signs of acute selenium poisoning in animals and humans include excessive salivation, garlic odour of the breath, shallow breathing, and diarrhea. Other signs of acute Se poisoning in animals include vomiting, dysponea, tetanic spasms, and death from respiratory failure.

Plants and animals raised in areas where selenium concentration is low in soils may develop diseases as a result of selenium deficiency. Deficiency of Se and vitamin E has been shown to cause muscular dystrophy in sheep and cattle, exudative diathesis in chickens, and liver necrosis in swine and rats. Signs specific for Se deficiency in the absence of vitamin E deficiency include pancreatic degeneration in chicks, and poor growth, reproductive failure, vascular changes, and cataracts in rats.

Selenium is considered a rare element because there are no large deposits anywhere in the world. It is mainly obtained as a by-product of the electrolytic refining of copper. Canada is among the leading producers of selenium in the world. According to Statistics Canada, Canada produced 286 000 kg Se in 1992. Selenium and its compounds are used in many products:

- in photoelectric cells (e.g., photographic exposure meters, photometers, counting devices, and light-controlled switches);
- as maroon and orange pigments, in combination with cadmium sulphide, for plastics and ceramics;
- in increasing the resistance of rubber to heat, oxidation, and abrasion (as an accelerator and vulcanizing agent in rubber production);
- as lubricants to increase the machinability of stainless steel;
- as an ingredient (selenium sulphide) in anti-dandruff shampoos for certain scalp conditions;
- as a constituent of fungicide (selenium sulphide);
- in glass manufacturing and as an alloy of steel and copper; and
- as an aid (e.g., radioactive selenium) in diagnostic medicine and in the visualization of certain malignant tumours.

The concentration of Se in natural waters is generally low, but varies widely. In seleniferous areas, Se levels are high and may exceed acceptable limits. In British Columbia, total Se concentration in rivers and streams is generally low at <1 µg/L; however, levels up to about 200 µg Se/L have been measured in areas contaminated by effluents from coal mines.

RECOMMENDED GUIDELINES

1 Drinking Water

It is recommended that the total concentration of Selenium in drinking water should not exceed 10 µg/L.

Rationale:

This guideline is consistent with the Health and Welfare Canada drinking water guideline, which was recommended to protect against the adverse health effects of selenium.

2 Aquatic Life

Freshwater:

To protect freshwater aquatic life from adverse effects, the average concentration[3] of total selenium should not exceed 2 µg/L in the water column, 2 µg/g dry weight in the sediment, and 1 µg/g wet weight/body weight in the tissue.

Rationale:

The 2 µg/L guideline for the water column will protect aquatic life both from direct toxic effects and from accumulating undesirable levels of

[3] The average concentration may be based on at least five weekly samples taken over a 30-day period in the water column or five tissue or sediment samples taken during a single sampling event.

selenium via the food chain. The guideline to protect from direct toxicity of selenium was based on the lowest observed effect level (LOEL) of 10 µg Se/L and a safety factor (SF) of 5, which is lower than 10 recommended in the CCME protocol. This choice for the lower SF was in recognition of the fact that: (a) selenium is an essential element for animal health, and (b) food (and not water) is the major source of selenium in the food chain.

The tissue and sediment guidelines are designed to protect from Se bioaccumulated through the food chain. They are based on three factors: (a) safe levels of the substance in tissues and sediments, (b) potential for Se to bioaccumulate in the aquatic environment, and (c) sediment Se-water column Se relationships. Therefore, they are consistent with the recommended water column guidelines. However, they are interim in nature at this time because there were insufficient data in the literature for a full guideline according to the CCME protocols for the sediment and tissue residue guidelines.

The recommended water quality guideline replaces the 1987 CCME guideline of 1 µg Se/L in the water column, which was based on the International Joint Commission (1981) recommended numerical limit for the Great Lakes. CCME did not recommend sediment or a tissue residue guidelines to protect freshwater life.

Marine water:

To protect marine aquatic life, the average concentration of total selenium should not exceed 2 µg/L.

Rationale:

The recommended guideline was based on the lowest observed effect level

(LOEL) of 10 µg/L in the growth of a red alga (*P. cruentum*) and the Pacific oyster (*C. gigas*) exposed to selenium and a safety factor of 5. The reasons for choosing the safety factor of 5 are the same as stated in the freshwater section.

The sediment and tissue guidelines for marine environments are the same as recommended for the freshwater life. There were not sufficient data in the literature to derive independent sediment and tissue guidelines for marine environments. However, the available data in the literature presented some evidence that will support the application of the freshwater guidelines to marine environments.

CCME (1987) did not recommend selenium guidelines to protect marine life.

3 Wildlife

To protect wildlife from adverse effects, the average concentration of total selenium should not exceed 4 µg/L.

Rationale:

The recommended guideline was designed to protect avian species exposed to selenium in the food chain. This guideline was based on relationship of selenium in the water column and in eggs of avian species that reside and feed on the aquatic environment.

An average alert level of 7 µg Se/g dry weight in eggs (or 1.4 mg Se/g wet weight, assuming 80% moisture content) is recommended to assess the site-specific effects of selenium to avian life in the environment. This alert level

was based on reported selenium concentrations in avian eggs from contaminated (EC_{10} concentration) and uncontaminated environments.

CCME did not recommend a water quality or a tissue (eggs) guideline to protect wildlife against the adverse effects of selenium.

4 Irrigation

The average concentration of total selenium in irrigation water supplies should not exceed 10 µg/L.

Rationale:

The recommended guideline was based on the lowest observed effect concentration (LOEC) of 2.5 µg/g dry weight of selenium in soil causing a lower yield in wheat grain. The CCME (1993) protocol was used to calculate a species-specific maximum acceptable toxicant concentration (or the guideline) to protect agricultural crops from adverse effects of selenium in irrigation waters.

The recommended guideline replaces the CCME (1987) guidelines of 20 µg Se/L for continuous use and 50 µg Se/L for the intermittent use on all soils.

5 Livestock Watering

To protect livestock water use, the average concentration of total selenium in livestock water should not exceed 30 µg/L.

Rationale:

The guideline was based on adverse effect of selenium on pigs, which

appears to be the most sensitive livestock species to selenium effects. An average concentration of 0.5 µg/g is considered to be safe for pigs exposed to selenium in diet (dry weight). The CCME (1993) protocol was used to derive the recommended guideline.

The recommended guideline replaces the CCME (1987) guideline of 50 µg Se/L.

APPLICATION OF GUIDELINES FOR AQUATIC LIFE

SELENIUM is ubiquitous in the environment. Its impact on the environment depends upon several factors related to Se sources and environmental variability. Therefore, care must be exercised when the water quality guidelines are applied to assess environmental impacts of selenium.

1. ASSESSMENT OF EXISTING WATER QUALITY

Selenium is present in the environment in both organic and inorganic forms. In aquatic environments, dissolved selenium binds or combines with organic particulate matter and subsequently settles in the sediment. This is especially true in slow-moving water or a lake. Such environments can build up large deposits of organic-rich selenium that are conducive to further storage and remobilization of Se through the benthic-detrital food web and rooted plants. The water quality guidelines recommended in this document recognize this issue and, therefore, should be protective of aquatic life in lentic environments.

In fast-flowing waters (e.g., streams and rivers), however, accumulation of selenium through the food chain is often inefficient because of the lack of rooted plants and organic-rich sediment. Bioaccumulation of selenium from water alone is not considered to be as significant as from the food chain. Site-specific assessment of the environment (e.g., sediment selenium levels, etc.) may be desirable, since the recommended guideline may be over-

protective in such situations.

The water quality guidelines recommended in this document are primarily based on data collected under controlled conditions, using species adapted to different climate conditions. Selenium has been shown to interact with other elements, which may result in reduced or enhanced Se toxicity. Also, the characteristics of organisms indigenous to British Columbia may differ from those of the species tested in the literature, with regard to selenium bioaccumulation potential and toxicity. Additional assessment techniques may be required to address such issues, including measurement of Se concentrations in fish and/or sediment and long-term bioassays with resident species using local waters. Long-term bioassays are complex and costly; they are likely to be undertaken for waterbodies with high resource values, which are threatened by controllable point sources of selenium pollution.

2. SETTING OF WATER QUALITY OBJECTIVES

As noted above, selenium toxicity in aquatic environments depends upon many factors. Also, the potential for selenium bioaccumulation through the food web may vary in lentic (still or slow-moving water) and lotic (fast-flowing water) environments. Furthermore, it has been noted that in certain natural environments fish can tolerate selenium concentrations that may exceed those found to be toxic in other environments or in the laboratory. Obviously, in such environments, there will be a need to develop site-specific water quality objectives to account for local environmental conditions. However, in a given watershed, both lotic and lentic conditions can be found simultaneously. A site-specific water quality objective protective of the most sensitive environment should be preferred option in such situations.

When concentrations of selenium in undeveloped waterbodies are less than the recommended guidelines, then more stringent values, if justified, could apply. In some cases, socio-economic or other factors (e.g., higher background levels) may justify objectives that are less stringent than the guidelines. Site-specific impact studies would be required in such cases.

3. SEDIMENT-WATER COLUMN RELATIONSHIP

The recommended sediment guideline assumed that sediment-Se and water column-Se content was related and was consistent at 5% total organic content (TOC). Obviously, this sediment-Se guideline may change as TOC changes. For lotic (rivers and streams) environments, an appropriate guideline may be calculated using the following relationship:

$$ln\ Sse = 0.657\ [ln(Wse * TOC)] - 0.877$$

where *ln* is natural logrithm, Sse is selenium in sediment (µg/g dw), Wse is selenium in the water column (µg/L), and TOC is percent total organic carbon in sediment. The validity of this relationship in lentic (lake) environments has not been tested in the literature. As noted above, the use of this relationship is paramount on the sensitivity of the entire system, including the lakes and reservoirs.

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Ministry of Water, Land and Air Protection

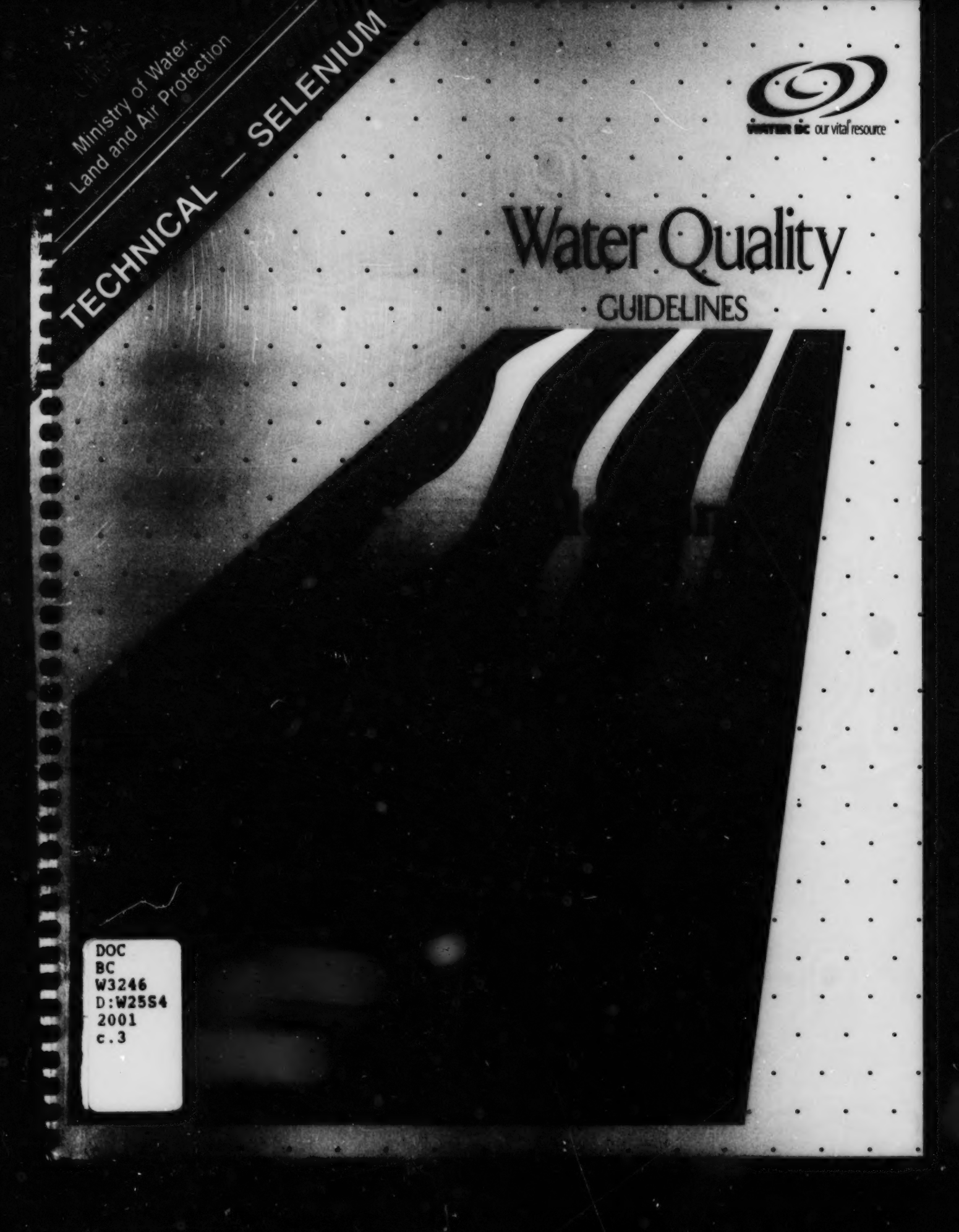
Ministry of Water, Land and Air Protection

TECHNICAL — SELENIUM

water BC our vital resource

Water Quality

GUIDELINES



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WATER QUALITY GUIDELINES FOR SELENIUM

Technical Appendix

September 2001

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1 Summary of Recommended Guidelines

Table 1.01 Recommended Water Quality Guidelines for Selenium

Water use	Guideline (mg/L)
Drinking Water	0.010 mg/L
Recreation and Aesthetic	Insufficient Data
Aquatic Life	
- Freshwater	0.002 mg/L
- Marine water	0.002 mg/L
- Sediment (interim)	0.002 mg/g dw
- Tissue (interim)	0.001 mg/g bw ww
Wildlife	0.004
Irrigation Water	0.010
Livestock Watering	0.030
Industrial Water	Insufficient Data

2 Introduction

Selenium (Se) is both beneficial and toxic to animals, plants, and humans. Selenium poisoning due to an excessive exposure has been well documented in the literature. Selenium poisoning was reported in livestock in western China as early as 1295, and in livestock, chickens, and children in Columbia, South America, in 1560 (Eisler 1985).

2.1 Physical and Chemical Properties

Selenium has an atomic number of 34, melting point (gray) of 217 °C, boiling point (gray) of 684.9 °C, and specific gravity ranging from 4.28 (vitreous) to 4.79 (gray) (Chemical Rubber Co., CRC, 1968). As a member of Group VIa of the periodic table, it is located between non-metallic sulphur and metallic tellurium. Naturally occurring stable isotopes include ^{74}Se (0.87%), ^{76}Se (9.02%), ^{77}Se (7.58%), ^{78}Se (23.52%), ^{80}Se (49.82%), and ^{82}Se (9.19%), resulting in a composite molecular weight of 78.96 (Adriano 1986).

Selenium can be prepared either with an amorphous or crystalline structure. The colour of amorphous Se is either red (in powder form) or black (in vitreous form). The crystalline monoclinic form of Se is deep red in colour while the crystalline hexagonal variety, the most stable form of Se, is metallic gray. Selenium is a member of the sulphur family and resembles sulphur both in its various forms and its compounds (CRC 1968).

Selenium, like sulphur, exists in the 2⁻ (Se^{-2} or selenide), 0 (Se^{0} or elemental Se), 4⁺ (SeO_3^{-2} or selenite), and 6⁺ (SeO_4^{-2} or selenate) oxidation states. Each oxidation state exhibits different chemical behaviour. The concentration, speciation, and association of Se in a given environment depend upon pH and redox conditions, the solubility of its salts (selenates are more soluble than selenites), the complexing ability of soluble and solid ligands, biological interactions, and reaction kinetics. Selenide and elemental Se occur in acidic, reducing, and organic-rich environments. Metallic selenides, Se-sulphides, and elemental Se are insoluble, and therefore, biological unavailable. For the pH and redox conditions of most soil and aquatic environments, SeO_3^{-2} and SeO_4^{-2} should be the dominant forms of Se (McNeal and Balistrieri 1989).

2.2 Production and Uses

Selenium is considered a rare element because there are no large deposits anywhere in the world. It is mainly obtained as a by-product of the electrolytic refining of copper. Canada, Japan, United States of America, Mexico, Sweden, and Belgium are among the leading producers of selenium (Adriano 1986). According to Statistics Canada, the quantities of Se produced in Canada were 321 000 kg in 1988, 369 000 kg in 1990, 227 000 kg in 1991, and 286 000 kg in 1992 (Canada Year Book 1994).

Compounds of selenium are used in many ways:

- in photoelectric cells (e.g., photographic exposure meters, photometers, counting devices, and light-controlled switches);
- as maroon and orange pigments, in combination with cadmium sulphide, for plastics and ceramics;
- in increasing the resistance of rubber to heat, oxidation, and abrasion (as an accelerator and vulcanizing agent in rubber production);
- as lubricants to increase the machinability of stainless steel.
- Selenium sulphide is also used as a catalyst in the preparation of pharmaceuticals including niacin and cortisone, as an ingredient in anti-dandruff shampoos (selenium sulphide) for certain scalp conditions, and as a constituent of fungicides (selenium sulphide).
- Radioactive selenium is used in diagnostic medicine and aids in the visualization of difficult-to-study malignant tumours.
- Selenium is also used in glass manufacturing and as an alloy of steel and copper (Adriano 1986, USDHHS 1994).

In the early 1900s selenium was used as a pesticide to control cotton pests, mites and spiders that attack citrus, and mites that damage apples. The use of selenium pesticides has been discontinued, due to their stability in soils and the resultant contamination of food crops, their high price, and their proven toxicity to mammals and birds (Eisler 1985).

3 Environmental Occurrences and Concentrations

3.1 Sources

3.1.1 Natural Sources

Selenium is inconsistently dispersed in geological materials; however, it is widely distributed in the environment and ranks 68th in earth crust abundance among elements (Adriano 1986).

Volcanic emanations and metallic sulphides associated with igneous activities are primary sources of Se in nature. Secondary sources include biological pools in which Se has accumulated. In general, shales have the highest concentrations of Se that is partly attributed to biological activity. Fifty Se minerals are known, but Se is commonly associated with heavy metal sulphides where it occurs as selenide (Se^{-2}), or as a substitute ion for sulphur in the crystal lattice (Adriano 1986).

'Seleniferous' soils or soils containing Se well above the normal levels are found in the arid and semi-arid areas of the world, including the western areas of Canada and the United States. In general, high-Se soils do not occur in humid regions (Adriano 1986).

Mosher and Duce (1987) estimated that 6 000 000- 13 000 000 kg of Se are annually released to the atmosphere from natural sources with 60-80% of the emissions being of marine biogenic origin. Nriagu (1989) suggested that natural sources contribute 700 000- 18 100 000 kg/a of Se to the atmosphere. Selenium contributions from individual natural sources were as follows: 0- 400 000 kg/a from wind-borne soil particles, 0-1 100 000 kg/a from sea salt spray, 100 000 -1 800 000 kg/a from volcanoes, 0-500 000 kg/a from wild forest fires, and 600 000- 14 300 000 kg/a from biogenic processes.

3.1.2 Anthropogenic Sources

Anthropogenic sources of selenium include fuel (coal and oil) combustion, primary and secondary non-ferrous metal industries, waste (domestic, municipal, and industrial) disposal and incineration, manufacturing processes, mining, smelting, refining, and steam electric[1].

Combustion of coal and other fossil fuels is the primary source of airborne selenium compounds (USDHHS 1994). Incineration of rubber tires, paper, and municipal waste also contribute to atmospheric selenium. Hashimoto *et al.* (1970) reported that rubber tires contained 1.3 mg Se/kg. Seventy different kinds of paper were found to contain selenium (West 1967). Other sources of atmospheric Se include microbial action within the soil, plants and animals, fly

[1] Electric utilities that employ steam produced by burning fossil fuels for power generation.

ash ponds (through fugitive dust emissions), and emissions from manufacturing and processing facilities (USDHHS 1994). Nriagu and Pacyna (1988) estimated that the worldwide emission of anthropogenic Se to the atmosphere was 1 700 000-5 800 000 kg/a. The major sources of emissions included coal combustion (900 000-2 800 000 kg/a), oil combustion (100 000-800 000 kg/a), primary non-ferrous metal industry (e.g., mining, and Pb, Cu-Ni, and Zn-Cd production) (700 000-2 100 000 kg/a) and waste incineration (0-100 000 kg/a) (Nriagu and Pacyna 1988).

Surface water can receive selenium from the atmosphere by dry and wet deposition, from adjacent water, from surface runoff, and from subsurface drainage. Selenium is released during coal mining because of the oxidation of selenium-bearing pyrite (Dreher and Finkelman 1992). The total loading of Se to aquatic ecosystems (including rivers, lakes, and oceans) was estimated to be 10 100 000-71 900 000 kg/a. Of the five sources, atmospheric deposition (500 000-1 100 000 kg/a) contributed the least amount to the aquatic ecosystems. The contribution from other sources was determined to be as follow: 6 000 000-30 000 000 kg/a from steam electric; 3 300 000-21 000 000 kg/a from mining, smelting, and refining; 300 000-11 300 000 kg/a from waste disposal; and 0-8 500 000 kg/a from manufacturing processes (Nriagu and Pacyna 1988).

Nriagu and Pacyna (1988) estimated that the worldwide emission of selenium into soils was 6 000 000 to 76 500 000 kg/a. The individual sources, in decreasing order of importance, included bottom fly ash (4 100 000-60 000 000 kg/a), disposal of industrial waste (500 000- 13 000 000 kg/a), atmospheric deposition (1 300 000-2 600 000 kg/a), peat (agricultural and fuel uses- (up to 400 000 kg/a), wastage of chemicals (100 000 to 200 000 kg/a), and fertilizers (up to 100 000 kg/a).

3.2 Residues

3.2.1 Water

Selenium concentrations in aquatic environments are generally low, but they can vary widely. In seleniferous areas, selenium levels are naturally high.

Concentrations ranging from 0.00012 to 0.00044 mg Se/L have been reported in drinking water from worldwide sources (Eisler 1985). However, Yang *et al.* (1983) reported that the average selenium content of drinking water taken from selenium-rich area in China with a history of disease reported as chronic selenosis was 0.054 mg Se/L.

Highly variable levels of selenium were reported in wells of seleniferous areas in the USA, ranging from non-detectable levels to 0.330 mg Se/L (Smith and Westfall 1937). Selenium concentrations in 107 irrigation and 44 livestock well waters in the San Joaquin area of California exceeded 0.01 mg Se/L in 26 wells, and 0.02 mg Se/L in 11 wells. The maximum concentration was 0.272 mg Se/L (Oster *et al.* 1988).

Under the Canada-British Columbia (BC) agreement on water quality monitoring, trace

metal concentrations were measured in various rivers of British Columbia. The total Se concentration in the BC rivers was generally low and ranged up to 0.001 mg Se/L in unmineralized to 0.009 mg Se/L in highly mineralized ambient environments. The concentration in a coal mining area ranged up to 0.0025 mg Se/L. The following table summarizes the results of the BC data.

Site	Total Se (mg/L)	Environment/Reference
Fraser River at Red Pass	*0.0003*	*Ambient (Wipperman and Holms 1996a,b,c)*
Fraser River at Hansard	*0.0004*	*Same as above*
Fraser River at Maruerite	*0.0006*	*Same as above*
Moyie River at Kingsgate	*0.0002*	*Ambient (Webber and Wipperman 1996)*
Kettle River	*0.001*	*Ambient (Webber and Pommen 1996a,b,c)*
Okanagan River at Oliver	*0.0009*	*Same as above*
Elk River at HWY 93 bridge	*0.0025*	*Coal mining area (Wipperman and Webber 1996)*
Bear River	*0.005*	*Highly mineralized area (Webber 1996a,b)*
Salmon River	*0.009*	*Same as above*

Anderson *et al.* (1994) reported trace metal levels from six sites in the Battle River, located in East-Central Alberta and West-Central Saskatchewan. The total Se concentrations were below the detection limit (0.0001 mg/L) at two of the six sites. Measurable concentrations at <0.0002 mg Se/L were reported for other sites. The highest concentration measured in the basin was 0.001 mg/L at a site that was mainly influenced by agriculture and oil and gas exploitation.

Adams and Johnson (1977) reported selenium concentrations ranging from 0.000001 to 0.000036 mg Se/L in the Great Lakes. In the lake water, in the vicinity of the nickel-copper smelter in Sudbury, Ontario, Nriagu and Wong (1983) reported concentrations of 0.0001 to 0.0004 mg Se/L.

In the U.S.A., Canton and Van Derveer (1997) reported average selenium concentrations of 0.018 mg/L and 0.0235 mg/L in some tributaries of the Arkansas River, Colorado. The high Se concentrations in these tributaries were primarily a result of natural weathering of Cretaceous marine shales and shale-derived soils.

In seawater, concentrations of selenium were reported to range from 0.000009 to 0.00045 mg Se/L (Ebens and Shacklette 1982, Whittle *et al.* 1977).

3.2.2 Sediments and Soils

All concentrations in this section are reported on a dry-weight (dw) basis.

Selenium concentration in soils is highly variable. The average concentration of Se in soils based on data collected from various countries was quoted to range up to 2 mg/kg (Kabata-Pendias and Pendias 1984). Background levels of Se in some Canadian soils were reported to

range from 0.03 to 2 mg/kg (McKeague and Wolynetz 1980). However, concentrations ranging from 80 to 90 mg/kg have been measured in seleniferous soils (Adriano 1986). Seleniferous soils of North America extend into Alberta, Manitoba, and Saskatchewan. In these soils, levels ranging from 0.1 to 6 mg Se/kg have been reported (Byers and Lakin 1939). More recently, Mermut *et al.* (1996) reported Se levels in Saskatchewan surface soils that ranged from 7.1 to 10.3 mg/kg.

Anderson *et al.* (1994) measured trace metal levels in the sediments of the Battle River, located in East-Central Alberta and West-Central Saskatchewan. The mean selenium concentrations at the six sites ranged from 0.023 to 0.402 mg/kg. The highest value of 0.402 mg Se/kg was reported for the site that was located near the headwaters; this site was least affected by human activity, although there is substantial oil and gas exploitation in this area.

Nriagu and Wong (1983) reported that in lake sediments, in the vicinity of a nickel copper smelter (Sudbury, Ontario), the selenium concentration ranged from 2 to 6 mg/kg. The lake sediment 240-km south from Sudbury recorded lower concentrations: 1 to 3 mg Se/kg.

3.2.3 Biota

Anderson *et al.* (1994) measured trace metal levels in invertebrates and aquatic plants of the Battle River of Alberta and Saskatchewan. The mean selenium concentration in the invertebrates (Amphipoda, Sphaeriidae, Unioidae, and Gastropoda) ranged from 0.2 to 1.6 mg Se/kg dry-weight. The highest concentration of 4 mg Se/kg dry-weight was recorded for unioidae at the site that was located near the mouth of the river and was mainly influenced by agriculture. The results for macrophytes (*Potamogeton richardsonii* and filamentous green algae) produced selenium concentrations that ranged from 1.3 to 25.3 mg Se/kg dry-weight in the algae, 0.9 to 3.5 mg Se/kg dry-weight in the stems and leaves of *P. richardsonii*, and 7.7 to 243 mg Se/kg dry-weight in the rhizome of *P. richardsonii*. The maximum concentration of 243 mg Se/kg dry-weight in the *P. richardsonii* rhizome was measured at the site located downstream from an area with active surface coal mining and a coal-fired power generating plant. These investigators also reported selenium levels in white sucker and northern pike caught from the Battle River. The concentration in the muscle tissue of these fish ranged from <0.007 (method detection limit) to 0.023 mg Se/kg wet-weight.

3.2.4 Analytical methods for water

Several techniques are in use to measure selenium in water. They include (a) atomic absorption methods (e.g., hydride generation/atomic absorption spectrometric and electrothermal atomic absorption spectrometric), atomic emission methods (e.g., inductively coupled plasma), and (c) chemical methods that involve conversion of selenite and determination of the organic derivative by colorimetry or fluorometry (Standard Methods 1992). The hydride generation or electrothermal atomization, colorimetric, and fluorometric are among the most sensitive methods, and the continuous hydride generation method is the method of choice for its

simplicity, reproducibility, and low detection limit (Standard Methods 1992).

The estimated detection limit for the atomic absorption methods is 0.002 mg Se/L. However, an increase in sensitivity may be achieved by using a larger sample volume, by reducing the flow rate of the purge gas, or by using gas interrupt during atomization. Quartz atomization cells provide for the most sensitive selenium hydride determination and minimize background noise associated with the argon-air entrained-hydrogen flame. The modified hydride-generation method (#02-2200) employed by the National Laboratory of Environmental Testing in Burlington, Ontario has produced a detection limit of 0.0001 mg/L for selenium in water (Manual of Analytical Methods1994).

4 Environmental Fate and Persistence

Selenium is present in the environment in both organic and inorganic forms. The organic form originates from partially decayed seleniferous vegetation. Its form generally determines the mobility and availability of Se in soils. Selenite (SeO_3^{-2}, Se IV) is the main mobile inorganic form of Se in soils of humid regions. Under alkaline conditions, Se is present as selenate (SeO_4^{-2}, Se VI), which does not form highly insoluble salts or stable complexes with sesquioxide. The low solubility of Se in acid and neutral soils can be attributed to its presence as selenite in combination with ferric iron or basic ferric selenite, which is slightly soluble (Adriano 1986). Other soil properties that influence the mobility and solubility of Se in soils include: organic carbon, clay and $CaCO_3$ content, cation exchange capacity, allophane content, and free forms of SiO_2, Al_2O_3, and Fe_2O_3 (Adriano 1986).

Selenium also biomethylates, producing organic metabolites that are more volatile than the parent organic forms. Plants, fungi, bacteria, microorganisms, and animals can produce methylated forms of Se from inorganic and certain organic forms. Non-accumulator plants, such as cabbage and alfalfa, give off $(CH_3)_2Se$ or other volatile Se compounds, and accumulator species, such as *Astragalus racemosus*, produce dimethyldiselenide when exposed to selenite (Adriano 1986). The formation of methylated Se compounds by animals appears to be one mechanism for Se detoxification as the toxicity of dimethyl selenide is 500 to 1 000 times lower than the toxicity of Se^{2-} (Vokal-Borek 1979).

Several microorganisms have been isolated that are capable of methylating inorganic Se. Conversion of selenite, selenate, and indigenous Se to volatile products was enhanced in soils amended with organic matter. Conversion of inorganic and organic Se compounds by microorganisms to volatile compounds, such as dimethylselenide and dimethyldiselenide, has also been observed in the lake sediments. Biomethylation products have also been detected in sewage sludge (Adriano 1986).

5 Bioaccumulation and Biomagnification

Bioaccumulation refers to the uptake of a contaminant from both water and food sources.

Biomagnification, on the other hand, means progressively higher concentrations when moving through successively higher trophic levels. Table 5.01 show bioaccumulation and bioconcentration factors obtained from the literture.

In aquatic environments, organisms accumulate selenium from both water and food. The bioaccumulation of selenium through the diet, however, is usually greater than the direct uptake from water, particularly when the Se occurs in natural dietary ingredients as compared to inorganic selenite or selenate (NAS 1980). Therefore, the toxic effects of food Se may be more significant than those of waterborne Se (Lemly 1985, Ohlendorf 1989).

Ohlendorf (1989) noted that the evidence for biomagnification of selenium through the food chain is contradictory. Lemly and Smith (1987) reported that selenium concentration in lower invertebrates or fish (whole-body basis) was two to six times the concentration in producers (i.e., phytoplankton, algae, and rooted plants) and sometimes up to 2 000 times the concentration in water.

In studying boron (B), molybdenum (Mo) and selenium (Se) in the aquatic food chain of the Lower San Joaquin River, California, Saiki *et al.* (1993) observed that the Se concentration was lower in filamentous algae than in invertebrates and fish. However, Se levels in or on detritus were similar to or higher than in invertebrates and fish. They concluded that Se in invertebrates and fish accumulated through food-chain transfer from Se-enriched detritus rather than from filamentous algae. Baudo (1983) stated that B, Mo, and Se did not exhibit evidence of biomagnification.

Sanders and Gilmour (1994) examined the transfer of selenium between bacteria and the ciliated protozoan, *Paramecium putrinum*, in laboratory cultures. The selenium concentration of ciliates was similar to that of their bacterial food on a dry-weight basis. These investigators concluded that selenium uptake by the ciliate occurred primarily during feeding and that biomagnification of selenium did not occur in this simple food chain.

Dobbs *et al.* (1996) exposed *Chlorella vulgaris, Brachionus calyciflorus, and Pimephales promelas* to 0, 0.110, 0.207, and 0.396 mg Se/L for 25 days in a flow-through system. The amount of Se in whole organisms was measured throughout the experiment. In this three-trophic level food chain, these authors found that bioconcentration factors were dependent on species, Se level, and length of exposure period, and they ranged between 100 and 1 000.

McDonald and Strosher (1998) monitored selenium mobilization from surface coal mining in the Elk River Basin, British Columbia. They found 100 to 200-fold increases in waterborne Se below the coal mines. However, levels in sediments, algae, and aquatic insects and fish tissue were only 2 to 5 times greater than the reference sites. The authors concluded that there was a limited amount of selenium bioaccumulation occurring in the fast-flowing Elk River. This conclusion was supported by a review of the literature conducted by Adams *et al.* (2000). The investigators found significant differences in the bioaccumulation of Se by fishes and invertebrates from lotic (flowing) and lentic (standing) water bodies. Bioaccumulation in fish is a factor of 10 or more higher in lentic systems as compared to lotic systems; these differences are function of selenium's site-specific biogeochemical cycling.

6 Carcinogenicity, Mutagenicity, and Teratogenicity

Earlier studies by Nelson *et al.* (1943) with seleniferous corn and wheat in the diet, by Schroeder and Mitchener (1971a) with sodium selenite or sodium selenate in drinking water, and by Volgarev and Tscherkes (1967) with sodium selenate in the diet, reported that selenium was carcinogenic in animals. However, subsequent studies revealed that the earlier studies were flawed and that there was no association between selenium intake and the incidence of cancer in humans and animals (USDHHS 1994). Also, in animals, selenium supplementation has been shown to significantly inhibit tumours induced by chemicals, viruses, or ultraviolet light (USDHHS 1994).

The only selenium compound that has been shown to be carcinogenic is selenium sulphide administered orally to mice and rats. Hepatocellular carcinomas and adenomas (in rats and mice), and alveolar/bronchiolar carcinomas and adenomas (in mice) were reported in the animals following chronic oral exposure to selenium sulphide (NTP 1980). Selenium sulphide is a pharmaceutical compound used in antidandruff shampoos. However, it is not absorbed through the skin and the use of shampoos containing this compound should be safe, unless one has cuts or sores on the scalp or hands. Chemically, selenium sulphide is very different from the organic and inorganic selenium compounds in foods and in the environment (USDHHS 1994).

According to the USEPA, selenium carcinogenicity in humans and rats is not classifiable. The evidence for selenium sulphide, however, is sufficient to classify it as a group B2 (probable human carcinogen) chemical (IRIS 1993).

7 Raw Water for Drinking Water Supply

7.1 Toxic Effects

Humans may be exposed to selenium through air, water and food. Those exposed to high air concentrations of selenium in industrial settings have reported dizziness, fatigue, and irritation of mucous membranes. In extreme cases, fluid in the lungs (pulmonary edema) and severe bronchitis have been reported (USDHHS 1994).

The severity of the effect of selenium in food and water depends on the amount ingested and the period of exposure. One 3-year-old boy died 1.5 hours after ingesting an unknown quantity of selenious acid contained in a gun-bluing preparation (Carter 1966). Clinical signs included excessive salivation, garlic odour of the breath, and shallow breathing. Death probably resulted from lung edema. A 15-year-old female survived ingestion of a solution of sodium selenate estimated to have provided 22.3 mg selenium/kg body weight, probably because she was forced to vomit soon after exposure (Civil and McDonald 1978). Clinical signs included garlic odour of the breath and diarrhoea.

A number of systemic effects including respiratory, cardiovascular, gastrointestinal, haematological, musculoskeletal, hepatic, renal, dermal, endocrine, and change in body weight has been reported in humans and animals exposed to selenium (USDHHS 1994). Contempre *et al.* (1991) reported a decrease in the level of thyroid hormone T4 in a cretin (person with marked mental deficiency) and normal schoolchildren treated with selenomethionine for 2 months. Jensen *et al.* (1984) reported both marked hair loss and the deformity, and loss of fingernails in a woman who had consumed super potent supplement tablets containing 31 mg total selenium (as sodium selenite and elemental selenium) per tablet for 77 days.

In an epidemiological study with a Chinese population living in an area with high selenium levels in soils and food, Yang *et al.* (1983) reported that the average dietary Se intake in this area of selenosis occurrence was estimated to be 3.2 mg Se/person/day (or 0.05 mg Se/kg body weight/day). In the subsequent follow-up study, Yang *et al.* (1989a) reported that the estimated daily dietary Se intake required to produce the selenium effects was at least 0.016 mg Se/kg body weight/day. Based on occurrence of these dermal effects, USDHHS (1994) derived a chronic minimum risk level of 0.005 mg Se/kg body weight/day. (A minimum risk level or MRL is an estimated daily human exposure to a dose of chemical that is likely to be without an appreciable risk of adverse non-cancerous effects over a specified duration of exposure).

Rosenfeld and Beath (1964) reported listlessness, a general lack of alertness, and other symptoms of selenosis in a family exposed for about three months to well water containing 9 mg Se/L (0.26 mg Se/kg body weight/day from drinking water). All symptoms disappeared after the use of seleniferous well water had been discontinued. These authors did not estimate the family's exposure to total dietary (water and food) selenium.

Roy *et al.* (1990) examined the concentration of selenium in sperm samples from 211 men. No significant correlation was found between the seminal plasma selenium concentration and sperm count or mobility. In a three-generation reproduction study, selenium administered as sodium selenate (0.57 mg Se/kg body weight/day) in drinking water of breeding mice produced adverse effects on reproduction. The most notable adverse effects included the failure of about half of the pairs to breed (Schroeder and Mitchener 1971b).

Little is known about the specific mechanism by which selenium and selenium compounds exert their toxic effects. The soluble compounds of sodium selenite and sodium selenate appear to be most toxic; on the other hand, elemental selenium and selenium sulphide are less toxic than most selenium compounds because of their extremely low solubility. It is generally theorized that acute toxicity is the result of selenium inactivating the sulfhydryl enzymes necessary for the oxidative reactions in respiration. Acute toxic effects such as swelling of the lung tissue result in respiratory failure and death. The lung, however, does not appear to be a target organ at lower levels of exposure (Mack 1990, USDHHS 1994).

Selenium can replace sulphur in biomolecules especially when the concentration of selenium is high and the concentration of sulphur is low in the organism. This may be a mechanism of selenium toxicity. Although selenocysteine appears to be specifically substituted for cysteine in glutathione peroxidase, selenomethionine appears randomly substituted for

methionine in protein synthesis. This may be an additional mechanism for intermediate or chronic toxicity (Stadtman 1983, Tarantal *et al.* 1991). Skin, hair, and nail damage are the most sensitive significant indicators of chronic selenium overexposure; however, the mechanisms causing these effects are not known. It has been hypothesized that the body uses nails and hair to excrete excess selenium (Yang *et al.* 1989b, USDHHS 1994).

7.2 Summary of Existing Guidelines

The current Canadian drinking water quality guideline is 0.01 mg/L for selenium (Health and Welfare Canada 1993). A drinking water quality guideline of 0.01 mg Se/L is also recommended by the World Health Organisation (1994) and many states in the U.S. (USDHHS 1994). The USEPA Office of Drinking Water recommended a maximum contaminant level of 0.05 mg Se/L in drinking water, whereas the U.S. Food and Drug Administration recommended a permissible level in bottled water of 0.01 mg Se/L (USDHHS 1994).

7.3 Recommended Water Quality Guidelines

It is recommended that the maximum concentration of selenium in drinking water should not exceed 0.01 mg/L. The recommended level is based on the Health and Welfare Canada's (1993) maximum acceptable concentration of 0.01 mg/L selenium in drinking water to protect from adverse health effects.

7.4 Human Exposure

Since selenium is naturally occurring and widespread, humans are exposed to low levels of selenium daily through food, water and air. The U.S. Department of Health and Human Services (1994) reviewed data found in the literature on human exposure (see below). It is quite obvious that most of these data are old and there is lack of recent data on the subject.

In the U.S., the average intake of selenium from food was estimated to range from 0.071 to 0.153 mg Se/person/day. Most of the daily intake came from eating cereals, grains, and meat. Measured average concentrations of selenium in the foods ranged from 0.004-0.083 mg/kg wet-weight in fruits, vegetables, and dairy products, 0.063-0.66 mg/kg wet-weight in grains and wheat bread, and 0.21-2.84 mg/kg wet-weight in meat, fish, and seafood. Seafood (e.g., 2.54 - 3.44 mg Se/kg wet-weight in swordfish), organ meats (1.45 - 2.32 mg Se/kg wet-weight in raw beef kidney) and Brazil nuts (0.2-253 mg Se/kg wet-weight, with an average value of 14.7 mg Se/kg wet-weight) contain the highest level of selenium (Schubert *et al.* 1987, Secor and Lisk 1989, USDHHS 1994).

Levels of selenium in drinking water are generally low. USDHHS (1994) estimated that less than 1% of the daily intake of selenium came from drinking water. Based on a review of selenium concentrations in different types of foods and the amounts of each type of food eaten,

Schubert *et al.* (1987) estimated a Se uptake of 0.071 mg Se/d for the U.S. population. Certain areas of Canada and the U.S. have highly seleniferous soils, and people living in these areas may be at risk of higher selenium exposure.

8 Recreational Water Quality and Aesthetics

8.1 Toxic Effects

Studies were not found in the literature concerning adverse effects of selenium on humans in water contact recreation (e.g., swimming). However, dermal effects (e.g., skin rashes, burns, and contact dermatitis) in humans have been reported for both acute and chronic exposure to selenium fumes and selenium dioxide (USDHHS 1994).

A 1988 case report described a female laboratory technician who developed severely puritic vesicles between her fingers after a 6-month exposure to media containing selenium. After 2 years, the severity of the symptoms increased to include eczema on the face and neck, watering eyes, and two asthma attacks. Sodium selenite or the broth containing selenium was the only positive patch tests (Senff *et al.* 1988). No effects were detected in eight women exposed daily for 2 weeks to a lotion containing up to 0.003 mg/kg selenium as L-selenomethionine designed to be used as an experimental sunscreen (Burke *et al.* 1992).

8.2 Summary of Existing Guidelines

Information o ecreational water quality guidelines for selenium was not found in the literature.

8.3 Recommended Water Quality Guidelines

A water quality guideline for selenium in recreational waters is not recommended because of the lack of information.

9 Aquatic Life

9.1 Toxicity to Aquatic Biota

Selenium toxicity to aquatic organisms is governed by several factors, including:

- form and concentration of selenium,
- type and characteristics (e.g., species and life stage) of organism,

- period and type of exposure to selenium (e.g., acute or chronic), and
- environmental factors (e.g., water hardness, temperature, presence of other substances, etc.).

Many studies have examined the acute and chronic effects of selenium in freshwater and marine biota. However, a great deal of variability exists in the quality of published data. Although many data were found in the literature, only the critical data were examined for the derivation of water quality guideline for the protection of aquatic life. The acute and chronic toxicity data for selenium obtained from the literature are summarized in Tables 9.01 to 9.10 and Figures 9.01 to 9.27. The discussion on acute effects include lethal and sublethal response data obtained on organisms exposed to selenium for ≤ 96 h; the section on chronic effects discusses lethal and sublethal chronic response data for organisms exposed for a period >96 h.

9.2 Freshwater Biota

9.2.1 Fish

(a) Acute Data

Table 9.01 and Figures 9.01 to 9.04 show that the acute toxicity to fish ranged from of 0.005 to 126.6 mg Se/L. Lemly (1983) reported a sublethal effect as a change in ventilatory rate or breathing activity at a concentration of 0.005 mg/L for both bluegill (*Lepomis macrochirus*) and largemouth bass (*Micropterus salmoides*). A sublethal effect, conditional avoidance, was also reported for goldfish (*Carassius auratus*) exposed to 0.25 mg/L selenite-Se (Weir and Hine 1970). However, the ecological significance of these data is difficult to determine because their impact on the population as whole is not well defined.

The 96-h LC_{50} ranged from 0.62 to 96.8 mg Se/L for several species of freshwater fish (Figure 9.03). The lowest selenite-Se concentration in water, causing 50% mortality in adult fathead minnows (*Pimephales promelas*), was reported to be 0.62 mg Se/L by the USEPA (1980) and Kimball (Cited in USEPA 1987). Halter *et al.* (1980) also reported a 96-h LC_{50} of 1 mg/L selenite-Se for adult fathead minnows at pH 7.3, 329 mg/L $CaCO_3$ water hardness, and 25 °C.

Figure 9.04 suggests that selenite-Se is more toxic than selenate-Se. This trend may be speculative, as selenate toxicity data are scant. Several studies have shown a clear difference in selenite-Se and selenate-Se toxicity. For instance, the results from studies with zebrafish (*Brachydanio rerio*) suggest that selenite is significantly more toxic than selenate (Niimi and LaHam 1975, 1976). Fifty percent mortality was observed in the fish exposed to either 20 mg/L selenite-Se or 82 mg/L selenate-Se. Hamilton and Buhl (1990) made similar observations with both coho salmon (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*). The swim-up fry (8-12 weeks) of coho salmon showed a 50% mortality at 7.8 mg/L of selenite-Se or 32.5 mg/L of selenate-Se; both tests conducted at pH 7.82, 12 °C, water hardness of 333 mg $CaCO_3$/L. These studies also indicated that the younger life stages of both coho and chinook salmon were more sensitive to the toxic effects. In their study, Hamilton and Buhl also demonstrated that, in

general, mixtures of selenate and selenite in the ratios of 3.5:1, 6:1, and 14:1 have similar acute toxicity values regardless of fish age. They concluded that the joint acute toxicity of these binary mixtures to the fish could be characterized as strictly additive.

(b) Chronic Data

The available data indicate that chronic toxicity of selenium ranged from 0.005 to 40 mg Se/L for several species of freshwater fish (Table 9.02 and Figures 9.05 to 9.07). Sorensen (1988) reported abnormalities of both liver and ovaries in redear sunfish (*Lepomis microlophus*) from Martin Lake that was contaminated with selenium at 0.005 mg Se/L. In a study conducted between 1975 and 1976, Cumbie and Van Horn (1978) reported complete reproduction failure for bluegill (*Lepomis macrochirus*), green sunfish (*L. cyanellus*), largemouth bass (*Micropterus salmoides*) and flat bullhead (*Ictalurus platycephalus*) from Belews Lake that had 0.01 mg Se/L at pH 7.5 and water hardness of 38.2 mg $CaCO_3$/L. A total of 29 species of fish in this lake decreased in standing crop from 86 680 to 27 099 g/ha for this same time period. Because the levels of selenium in the water were relatively low for the severity of the effects on the fish, it was hypothesized that these deleterious effects were a result of bioaccumulation through the food chain; the phytoplankton from two sites at Belews Lake contained an average of 15 to 70 µg Se/g dry-weight.

In a three-trophic level and a continuous flow-through test system, Dobbs *et al.* (1996) exposed alga (*Chlorella vulgaris*), rotifers (*Brachionus calyciflorus*), and fathead minnows (*Pimephales promelas*) for 25 days to various levels of selenium (0, 0.110, 0.207, and 0.396 mg Se/L). They found that the fathead minnow growth was impaired after seven days at 0.207 and 0.396 mg Se/L levels, with 100% mortality by day sixteen. A reduction in the fish biomass, compared to the control, was also apparent at 0.110 mg Se/L after day twenty.

In bluegills exposed to 0.005 mg Se/L in water at 20 °C and 5.1 µg Se/g dry-weight in their diet for 180 days, Lemly (1993) reported hematological changes and gill damage in the fish that reduced respiratory capacity while, at the same time, increasing oxygen consumption and respiratory demand. When these tests were conducted at a lower temperature of 4 °C, "Winter Stress Syndrome" was seen which was symptomised by an increase in stress-related energy demand, a reduction in feeding, and eventually death as a response to the shorter photoperiod and colder temperature.

Gillespie and Baumann (1986) studied bluegill larvae collected from crosses of adults from Hyco Reservoir with relatively high selenium in the water (0.009-0.012 mg Se/L) and in the diet (25-45 µg Se/g dry-weight), and adults exposed to much lower levels of selenium. They noted that the exposure to Se in the Hyco Reservoir resulted in larvae with gross abnormalities and general edema. They concluded that the symptoms seen in the larvae were due to selenium transferred to the egg from the female parent. Hermanutz *et al.* (1992) saw similar results with bluegills exposed to 0.01 mg Se/L in experimental streams, which affected both growth and survival of larvae and growth of adults. Schultz and Hermanutz (1990) conducted studies on fathead minnows (*Pimephales promelas*) which supported these conclusions, resulting in a high

incidence of lordosis and edema in larvae at water concentrations of 0.01 mg Se/L in experimental streams. These studies of the uptake of selenite in embryos after hatching, concluded that the high levels seen in embryos were not taken up from the water initially upon hatching, but were in fact passed on from the parent. Hermanutz (1992) observed abnormalities in his studies on the late juvenile and early adult development of fathead minnows from the effect of selenium in water (0.010 mg Se/L) and diet in an experimental stream.

DeFrost *et al.* (1999) reviewed residue-based selenium toxicity thresholds for freshwater fish. Based on the available literature, they felt that the scientific literature is not supportive of sediment or water thresholds. The reason for this was the site-specific factors that influence Se bioavailability, bioaccumulation, and toxicity in aquatic systems. They were, however, supportive of the tissue-based thresholds and proposed whole body thresholds of 9 mg/kg dw for warmwater fish and 6 mg/kg dw for larval coldwater anadromous fish, an ovary threshold of 17 mg/kg dw for warmwater fish, and fish dietary thresholds of 10 and 11 mg/kg dw for warmwater and larval coldwater anadromous fish, respectively.

Kennedy *et al.* (2000) studied the effect of elevated concentration of selenium (0.0133 to 0.0145 mg/L - caused by coal mining in the area) on wild cutthroat trout in the Elk River in southeastern British Columbia. The results were compared with the fish caught from the reference site with <0.001 mg Se/L in water. As expected, the Se concentration in females from the Se-elevated sites (e.g., 21.2 ± 20.2 µg/g dw in eggs) was much higher than those from the reference (e.g., 4.6 ± 1.8 µg/g dw in eggs). Despite the elevated egg Se concentrations, there was no significant effect on fertilization, time to hatch, percent hatch, or egg, larvae, and fry deformities or mortalities. The investigators concluded that the lack of any toxic response might be due to an evolved tolerance of the fish to high levels of selenium in the seleniferous river system.

Figure 9.07 shows a possible trend in selenite being more toxic than selenate. However, available data were scant and no comparative studies were found in the literature.

9.2.2 Invertebrates

(a) Acute Data

The acute toxicity of selenium ranged from 0.006 to <200 mg Se/L for several species of freshwater invertebrates (Table 9.03 and Figures 9.08 to 9.11). A comparison between Figures 9.01 and 9.08 results indicated that selenium was more toxic to invertebrates than fish.

Malchow *et al.* (1995) reported significant reduction in larval growth of the midge (*Chironomus decorus*) exposed to 0.01 mg Se/L, as selenite or selenate, in water for a period of 96 hours. In their tests, they found that the larvae were feeding on algae (*Selenastrum capricornutum*) which had bioaccumulated selenium from water to concentrations of ≥2.84 µg selenite-Se/g dry-weight and ≥2.11 µg selenate-Se/g dry-weight, respectively. Algae had made selenium more available to the midge.

Ingersoll *et al.* (1990) reported a lower range of values for selenite-Se (7.95 to 14.6 mg/L) toxicity than for selenate-Se (10.5-16.2 mg/L) in 48-h LC_{50} studies, indicating that selenite may be slightly more toxic to the midge (*C. plumosus*).

Bringmann and Kuhn (1977b) exposed the water flea (*Daphnia magna*) to 0.01 mg Se/L as selenite for 24 h at a water hardness of 214 mg $CaCO_3$/L and reported a change in swimming ability in 50% of the organisms. The quality of these data could not be ascertained because the original source was not found.

Maier *et al.* (1993) studied mortality in the neonates of the water flea (*D. magna*) exposed to different forms of selenium in water at pH 8.2, dissolved oxygen (or DO) level of 8.6 mg/L, and 20 °C. The 48-h LC_{50}s were as follows: 2.84, 0.55, 0.31 and 2.01 for selenate-Se, selenite-Se, seleno-DL-methionine, and seleno-DL-cystine, respectively. These data show that organic forms of selenium are as toxic, if not more, as the inorganic forms. Immobilization as a sublethal acute response (or 48-h IC_{50}) was observed at concentrations of 0.045 mg/L for seleno-DL-methionine and 0.52 mg/L for seleno-DL-cystine. These investigators also reported that the presence of sulphate in water modified the toxicity of the different forms of selenium. An increase in sulphate concentration resulted in a decrease in toxicity for selenate, varied the toxic effects of selenite, and had no effect on the toxicity of seleno-DL-methionine. Johnston (1987) also showed higher toxicity for selenite than selenate, but the difference was less significant than that reported by Maier *et al.* (1993). The tests with adult water fleas at 22 °C and pH 8.4, yielded 96-h LC_{50} concentrations of 0.44 mg/L selenite-Se and 0.58 mg/L selenate-Se. More recently, Brasher and Ogle (1993) reported that the 96-h LC_{50} for the two-month old amphipod (*Hyallela azteca*) at pH 8.6, DO 7.7 mg/L, 25 °C, 133 mg $CaCO_3$/L hardness, and 302 mg $CaCO_3$/L alkalinity was three times lower with selenite-Se (0.676 mg/L) than with selenate-Se (1.868 mg/L).

Davis *et al.* (1988) reported that 0.006 mg Se/L as selenite resulted in 50% mortality of the cladoceran (*Daphnia pulicaria*) in 96 hours. The same results were obtained with water fleas (*D. magna*) exposed to 0.04 mg/L selenium as seleno-DL-methionine by these investigators. The 96-h LC_{50} of 0.006 mg/L selenite-Se was the lowest found in the literature.

Owsley (1984) and Owsley and McCauley (1986) showed that the Se toxicity differed between cladocerans (*Ceriodaphnia affinis*) whose parents were previously exposed to selenium (48-h LC_{50}=0.35 mg Se/L) and those which weren't (48-h LC_{50}=0.6 mg Se/L). Their tests were carried out at pH 7.9, DO 8.4 mg/L, 21.5 °C, and water hardness of 100.8 mg $CaCO_3$/L and suggested that the toxicity is passed from parent to offspring and this adds to accumulation.

(b) Chronic Data

The chronic toxicity of selenium ranged from 0.002 to 15 mg Se/L for several species of freshwater invertebrates (Table 9.04 and Figures 9.12 to 9.14). Davis *et al* (1988) reported a decrease in reproduction of the protozoan *Entosiphion sulcatum*, when exposed to 0.003 mg/L selenite-Se.

Crane *et al.* (1992) reported changes in abundance of some freshwater invertebrates tested with a 60:40 ratio of selenate-Se to selenite-Se in a 514-day study. Midges (*Chironomidae*) and water fleas (*Eurycercus lamellatus* and *Graptoleberis testudinaria*) were shown to have a decrease in abundance at concentrations 0.002 to 0.025 mg Se/L. The decrease in abundance was also observed between 0.010 and 0.025 mg Se/L for the water flea (*Chydorus ovalis*), and 0.025 mg Se/L for the water flea (*Acroperus harpae*), the parasitic copepod (*Ergasilus sp.*), and the tubificid worm (*Tubifex tubifex*). It was not apparent whether the decrease in abundance was due to a decrease in reproduction or in growth to adult stage.

Brasher and Ogle (1993) reported that the 10-d LC_{50} for the two-month old amphipod (*Hyallela azteca*) exposed to selenium was twice as high with selenate-Se (1.135 mg/L) than with selenite-Se (0.502 mg/L), at pH 8.6, DO 7.7 mg/L, 25 °C, 302 mg/L alkalinity, and 133 mg $CaCO_3$ hardness. Also, a significant reduction in the number of young per female was observed at a concentration of 0.20 mg/L selenite-Se, but no effect on reproduction was observed when exposed to 0.70 mg/L selenate-Se.

In a three-trophic level and a continuous flow-through test system, Dobbs *et al.* (1996) exposed an alga (Chlorella *vulgaris*), a rotifer (*Brachionus calyciflorus*), and a fish (*Pimephales promelas*) for 25 days to various levels of selenium (0, 0.110, 0.207, and 0.396 mg Se/L). They found that the rotifer population standing crop (measured as dry weight) was significantly reduced at 0.207 and 0.396 mg Se/L by day four and declined to below detection by day seven. A reduction in rotifer biomass, compared to the control, was also apparent at 0.110 mg Se/L after day twenty.

Boyum and Brooks (1988) reported that organically-bound selenium, when present in water with selenate-Se, significantly reduced the toxicity of the inorganic selenium by altering its rate of incorporation. The tests indicated that an exposure to 0.05 to 1 mg/L selenate-Se decreased the survival of *Daphnia magna* and reduced the number of offspring produced. When a dietary source of algae, grown in 0.05 to 1 mg/L selenate-S, was added to the test solution, the survival rate for the organisms increased. However, no offspring were produced at 1 mg Se/L, suggesting that reproduction is a more sensitive end point with a dietary source of selenium.

9.2.3 Algae and Macrophytes

The toxicity of selenium to freshwater macrophytes and algae varied from 0.01 to 99 mg Se/L (Table 9.05 and Figures 9.15 to 9.17).

Davis *et al.* (1988) reported a decrease in cell division for an alga (*Ankistrodesmus falcatus*) exposed to 0.010 mg Se/L as selenate. For the green alga *Selenastrum capricornutum*, Foe and Knight (Cited from USEPA 1987) reported a decrease in dry-weight and chlorophyll *a* at a concentration of 0.075 mg Se/L as selenite.

Kiffney and Knight (1990) exposed cyanobacteria (*Anabaena flos-aquae*) to seleno-L-methionine, selenate-Se, and selenite-Se for 10 days. The first sub-lethal effect, a decrease in

chlorophyll *a*, was observed at 0.1, 3.0, and 3.0 mg Se/L, respectively. Davis *et al.* (1988) reported that concentrations of 0.3, 5 and 4, respectively, for these same forms of selenium caused a decrease in cell division of the cynobacterium.

In a three-trophic level and a continuous flow-through test system, Dobbs *et al.* (1996) exposed an alga (*Chlorella vulgaris*), rotifers (*Brachionus calyciflorus*), and fathead minnows (*Pimephales promelas*) for 25 days to 0, 0.110, 0.207, and 0.396 mg/L selenium from selenate in natural creek water supplemented with nutrients to sustain algal growth. In an initial algal-screening test, they found that the algal growth rates were reduced at 0.082 and 1.053 mg Se/L, with no effect at 0.0085 mg Se/L. In the trophic test, the algal population showed evidence of reduced growth rates at 0.207 and 0.396 mg Se/L, but not at 0.110 mg Se/L.

Richter (1982) exposed the green algae *Selenastrum capricornutum* to selenate-Se and selenite-Se and reported 4-d EC_{50}s of 0.199 mg Se/L and 2.9 mg Se/L, respectively. Davis *et al.* (1988) reported a decrease in cell division of 20% for the same species of algae exposed to 0.1 mg/L selenite-Se. In a test solution containing 3.3 mg/L sulphate, Williams *et al.* (1994) reported a decrease in the growth (weight) of *S. capricornutum* at a concentration of 0.1 mg/L selenium as 4% selenite and 96% selenate. When the sulphate content of the test solution was raised from 3.3 to 33 mg/L, the bioaccumulation of selenium in the algae decreased significantly and the growth of the algae increased comparatively.

9.3 Marine Biota

Data are limited to assess the effects of toxicity on marine organisms.

9.3.1 Fish

(a) Acute Data

Acute toxicity of selenium to marine fish ranged from 0.6 to about 86 mg Se/L (Table 9.06 acute data only and Figures 9.18-9.21 that include both acute and chronic toxicity data). Cardin (1986) reported the lowest EC_{50} or LC_{50} value for the larvae of haddock (*Melanogrammus aeglifinus*) as 0.599 mg/L selenite-Se. The USEPA (1980) also reported 50% mortality in haddock (*M. aeglifinus*) exposed to a concentration of 0.6 mg Se/L for 96 hours.

In a study with striped bass (*Morone saxatilis*), Chapman (1992) exposed the fish to selenite-Se and selenate-Se during different life stages and conditions of inflated or uninflated bladder. The test conditions were: near saturation DO, 17 °C, 38.5 to 40.5 g/kg salinity, and 750 to 830 mg $CaCO_3$/L hardness. For 24-day old fish with an inflated bladder, the 96-h LC_{50}s were reported to be 26.3 mg/L selenite-Se and 3.4 mg/L selenate-Se, as compared to 36.7 mg/L selenite-Se and 3.0 mg/L selenate-Se for the fish with an uninflated bladder. Other life stages displayed similar trends. These results indicate that selenate is significantly more toxic to marine fish than selenite. This is opposite to what was found in fresh water. Figure 9.21 compares the

toxicity of various forms of selenium; unfortunately, only limited data were found in the literature.

(b) Chronic Data

The chronic toxicity data for marine fish were limited (Table 9.07 chronic data only and Figures 9.18-9.21 that include both acute and toxicity data). The lowest chronic toxicity value was obtained by Klauda (1985), who reported a significant incidence of developmental anomalies of the lower jaw in striped bass (*Morone saxatilis*) exposed to a concentration of 0.039 mg/L selenate-Se for 9 to 65 days. Also, a significant incidence of severe blood cytopathology was reported in the fish exposed to 1.29 mg/L selenate-Se. Klauda (1986) reported a high number of deformities in the striped bass exposed to a concentration of 0.09 mg Se/L during a period from post-hatch through 60 days.

Ward *et al.* (1981) reported that a concentration of 0.675 mg Se/L caused sublethal effects in sheepshead minnow (*Cyrinodon variegatus*) during early life stages.

9.3.2 Invertebrates

(a) Acute Data

The acute toxicity of selenium to marine invertebrates varied from 0.127 to less than 10 mg Se/L (Table 9.08, Figures 9.22-9.24 that includes both acute and chronic toxicity data).

In a life cycle test with opossum shrimp (*Mysidopsis bahia*), the USEPA (1980) reported an LC_{50} of 0.127 mg Se/L for the egg stage. Nelson *et al.*, (1988) reported that a concentration of 0.255 mg Se/L as selenite resulted in a 50% mortality of the bay scallop (*Argopectin irradians*).

Glickstein (1978) reported 30% mortality in the dungeness crab (*Cancer magister*) when exposed to 0.1 mg Se/L as selenite for a period of 96 hours; the mortality increased to 100% at 5.0 mg Se/L. There were no data available on the effects of selenate-Se in marine invertebrates.

(b) Chronic Data

Few chronic toxicity data were found in the literature for marine invertebrates (Table 9.09, Figures 9.22-9.24). Micallef and Tyler (1990) reported a reduction in filtration rates by 86-100% when the blue mussels (*Mytilus edulis*) were exposed to 0.05 mg Se/L in the laboratory. Ward *et al.* (1981) reported a life cycle chronic value of 0.212 mg/L selenite-Se for the mysid *Mysidopsis bahia*.

Wolfenberger (1986) studied selenium toxicity in the hermit crab (*Clibanarius vittatus*) at a concentration of 100 mg Se/L, as a function of temperature and salinity. It was reported that survival time decreased as temperature reached 20 °C and fluctuated, with no definite trend, with salinity between 10‰ to 40‰.

9.3.3 Algae and Macrophytes

Table 9.10 and Figures 9.25 to 9.27 show the toxicity of selenium to marine algae and macrophytes.

Studies by Wheeler *et al.* (1982) reported that the effects of selenium on algae depend on the type of algae, the concentration and form of selenium, and the concentration of sulphate. In experiments where the organisms were pre-treated with the sulphate concentration (850 mg/L) normally present in seawater, the most sensitive of the algae tested was the red alga (*Porphyridium cruentum*) which showed a decrease in growth at 0.01 mg/L selenate-Se. The growth of most of the other algae including the green algae *Dunaliella primolecta*, *Platymonas subcordiformis*, and *Platymonas sp.*, and the diatom *Tetraselmis chuii*, was reduced between 0.1 and 1.0 mg/L selenate-Se with the exception of the green algae (*Chlorella sp.*). A concentration of 10 mg/L selenate-Se was lethal in 4-5 days to all algae tested. However, when the organisms were pre-treated with a sulphate concentration of one-tenth the normal seawater concentration (i.e., 85 mg/L), Wheeler *et al.* (1982) found that the dose of 0.1 mg/L selenate-Se reduced the growth of some algae and was lethal to others. Also, a concentration of 0.01 mg/L selenate-Se improved the growth of most algae over the growth usually observed with an 85 mg/L sulphate concentration and no selenium added to the medium.

Figure 9.27 suggests that selenate is more toxic than selenite to marine algae and macrophytes. This corresponds with Figure 9.21 that shows the same trend with marine fish.

9.4 Interactions

Selenium interacts with several metals and non-metals in the environment. In reviewing interactions with various metals, Marier and Jaworski (1983) noted that selenium-interactive elements include metals that (i) are widely used for their conductance or electron-transfer properties in the electric field (e.g., copper, germanium, tungsten), (ii) have a strong affinity for sulphide (e.g., silver, mercury), or can, like Se, easily be reduced by metabolic processes (e.g., arsenic). Also, all elements do not interact with Se in a similar manner. For instance, antimony, copper, germanium, and tungsten alleviate selenium toxicity. Conversely, selenium counters the toxicity of cadmium, mercury (or methyl mercury), silver and thallium. Arsenic, on the other hand, is involved in both types of interactions.

Maier *et al.* (1993) studied the effects of varying sulphate concentration on the toxicity of selenate-Se, selenite-Se, and seleno-DL-methionine to *Daphnia magna*. They found that both the chemical form of selenium and the sulphate concentration influenced the toxicity of selenium. Increasing the concentration of sulphate decreased, varied, and left unaffected the toxicity of selenate-Se, selenite-Se, and seleno-DL-methionine, respectively. These investigators also concluded that (a) the toxicological interactions of the various forms of Se were additive, (b) there was a common uptake pathway for sulphate and selenate-Se with simple chemical

competition occurring, causing a decrease in selenate toxicity with an increase in sulphate concentration, and (c) there were separate pathways for selenite-Se and seleno-DL-methionine accumulation that were not affected by sulphate concentrations. Williams *et al.* (1994) also reported antagonism between sulphate and selenate-Se uptake and toxicity in the green alga *S. capricornutum*.

Paulsson and Lundbergh (1989) found that treatment of lakes with selenium over a period of three years reduced significantly the uptake of mercury by perch (*P. fluviatilis*), pike (*E. lucius*) and roach (*L. rutilus*). The Se levels achieved (at one metre depth) through treatment with sodium selenite ranged from 0.001 to 0.006 mg/L. These investigators also found that the fish accumulated high levels of Se in the tissue during the experiment. As a result, they recommended that for such amelioration procedures the selenium level should be strictly controlled at less than 0.005 mg/L. The investigator did not comment on the any adverse effects of the elevated Se levels in fish.

Gaikwad (1989) found that the toxicity of a mercury, copper, and selenium mixture was much higher than the toxicity of the individual metals.

9.5 Summary of Existing Guidelines

9.5.1 Freshwater Aquatic Life

The Canadian Council of the Ministers of the Environment (CCME, formerly CCREM 1987) has recommended a maximum water quality guideline of 1.0 µg/L total selenium to protect freshwater aquatic life in Canada.

The USEPA (1986) expressed their freshwater criteria for the protection of aquatic life in terms of total recoverable inorganic selenite. They recommended that the 24-hour average concentration should not exceed 35 µg/L, and the maximum concentration to eliminate acute effects should not exceed 260 µg/L at any time.

9.5.2 Marine Aquatic Life

To protect saltwater aquatic life, the USEPA (1986) recommended that the average concentration of inorganic selenite (total recoverable) should not exceed 54 µg/L in 24 hours, and the maximum concentration at any time should not exceed 410 µg/L. The Canadian Council of Ministers of the Environment (CCME) did not establish a selenium guideline to protect marine life.

9.6 Recommended Guideline and Rationale

9.6.1 Freshwater Aquatic Life

It is recommended that the maximum concentration of total selenium in water for the protection of freshwater aquatic life should not exceed 0.002 mg Se/L.

For the protection of aquatic life, it is also recommended that total selenium in the sediment and fish tissue should not exceed 2 µg/g dry weight and 1 µg/g body weight (wet weight), respectively. The sediment guideline will apply to sediments with total organic content of 5%. The sediment and tissue guidelines are interim thresholds that provided the basis for the recommended water quality guideline. Full guidelines will be proposed for these media at a later date using the appropriate protocols.

9.6.2 Marine Aquatic Life

To protect aquatic life in marine environments, it is recommended that the maximum concentration of total selenium in water should not exceed 0.002 mg Se/L.

9.7 Rationale

9.7.1 Freshwater Aquatic Life

Three approaches were used to derive a guideline that will protect freshwater aquatic life from the adverse effects of selenium in water. The proposed guideline of 2 µg Se/L was within the range justified in the arguments presented below. This concentration will protect aquatic life in the most sensitive environment of lakes and reservoirs from the adverse effects of Se in water.

A. Water Concentration Approach

In a semi-natural ecosystem of experimental streams, Hermanutz (1992) indicated that a concentration of 0.01 mg Se/L resulted in malformation of late juvenile and early adult fathead minnows. An exposure to 0.01 mg Se/L also caused edema and lordosis in fathead minnow embryos, and reduced adult growth and reproduction in (Schultz and Hermanutz 1990, Hermanutz *et al.* 1992). In Hyco Reservoir, which was contaminated with effluent from coal-fired power plants, Gillespie and Baumann (1986) found reproduction failure in bluegill and deformity in larvae that were exposed to a Se concentration ranging between 0.009 and 0.012 mg Se/L. Cumbie and VanHorn (1978) observed mortality, deformity, and a reduction in standing crop of threadfin shad, flat bullhead, green sunfish, bluegills and largemouth bass in Belews Lake. Complete reproduction failure was also seen in bluegills and largemouth bass. The concentration of selenium was found to be 0.01 mg Se/L in the main lake. Bringmann and Kuhn (1977b) reported a 24-h EC_{50} (swimming) of 0.010 mg Se/L for *D. magna*.

The aquatic systems of Hermanutz (1992), Hermanutz *et al.* (1992), Schulltz and

Hermanutz (1990), Gillespie and Bauman (1986), and Cumbie and VanHorn (1978) can be characterized as standing or slow moving with low flushing rates. Such systems can build up large deposits of organic-rich sediment that can serve as a site for Se storage and remobilization through the benthic-detrital food web and rooted plants (Canton and Van Derveer 1997). Therefore, for derivation of the proposed guideline, it was assumed that the organisms in the above studies were exposed to both Se in water as well as from food sources. (The authors, however, did not state the selenium concentration in foods consumed by the organisms). Furthermore, it was also assumed that in these aquatic systems, the selenium concentrations in the water column and the internal food sources was in equilibrium.

Based on the lowest observed effect level of 0.01 mg Se/L and a safety factor of 5[2], a guideline of 0.002 mg/L of selenium was proposed to protect aquatic life in fresh water.

Several studies reported adverse effects of selenium on aquatic life at concentrations below 0.01 mg Se/L (see below). These studies were not considered in the derivation of the proposed water quality guideline. The reasons for their rejection were several-fold:

- they lacked details about the data and their original source (e.g., Davis *et al.* 1988);
- they failed to provide details on experimental methodology (re: Se effects), which made the data suspect (Hyne *et al.* 1993);
- chronic endpoints were indefinite or could have been influenced by factors other than those considered in the study (e.g., Crane *et al.* 1992), and
- test organisms, while exposed to waterborne selenium, were also fed a diet containing selenium (an external source of selenium; e.g., Lemly 1993, Alaimo *et al.* 1994).

Crane *et al.* (1992) and Hyne *et al.* (1993) reported the lowest observed effect level for selenium at 0.002 mg /L. In the former study, the authors reported a decrease in abundance in several invertebrates exposed to Se for a long period of time (about 1.5 years); these results could have been influenced by other factors such as predation. The latter study with daphnia (*Moinodaphnia macleyi*) had very little information in the source paper about materials and methods used in the experiment. Davis *et al.* (1988) reported that 0.003 mg Se/L decreased reproduction in the protozoan *E. sulcatum* and 0.006 mg Se/L as a 96-h LC_{50} for the cladoceran *D. pulicaria*. However, this paper was a review of the literature and the original sources of data were not reported. Sorensen (1988) reported that a waterborne concentration of 0.005 mg Se/L caused substantial alterations in the livers (necrosis, cytoplasmic, vacuolation, etc.), as well as in the ovaries (atretic follicles, connective tissue hypertrophy, etc.), of redear sunfish. These

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[2] CCME (1991) recommended a safety factor (SF) of 10 to derive a water quality guideline from chronic data. Instead, a smaller safety factor of 5 was used because selenium is recognized as a substance with a small effect concentration to background concentration ratio. Furthermore, the SF of 10 will yield a guideline that is at the background level (~1µg/L) or will fall below it in certain mineralized area (Webber 1996a,b). Another argument in favour of a lower safety factor was based on the Canton (1999) and Canton and Van Derveer (1997) observations. These investigators pointed out that while the 10 µg/L selenium in the main Belews Lake water was toxic to the fish, no discernable selenium toxicity to fish was apparent in the arm of the lake that contained 5 µg Se/L.

endpoints were not accepted for the derivation of water quality guidelines because their ecological significance could not be ascertained. Lemly (1993) reported hematological changes and gill damage in bluegills exposed to a waterborne concentration of 0.005 mg Se/L. This study was rejected because the fish were also fed an external diet containing 5.1 µg Se/g (dry-weight).

B. Tissue Concentration Approach

In an aquarium study, Hamilton and Wiedmeyer (1990) reported no-effect concentrations of 35 µg/L and 70 µg/L total selenium for growth and survival of chinook salmon in both freshwater and well water. This no-effect waterborne concentration range was considered to be equivalent to a no-effect, whole-body selenium concentration of 3-5 µg/g body weight (bw) on a dry weight (dw) basis in well water and 2-4 µg/g bw dw in freshwater. The threshold of 3-5 µg Se/g bw on a dry weight basis was corroborated by Hamilton *et al.* (1990) in a feeding study with chinook salmon. Brix *et al.* (2000) combined Hamilton *et al.* (1990) data with similar data from the literature and reworked them using sophisticated statistical procedures. They, then, proposed a whole-body toxicity threshold (EC10) of 6 µg/g dw for the chinook salmon based on the 60-day exposure data. Assuming 80% moisture content, the safe level on a wet weight (ww) basis was determined to be 1.2 µg Se/g ww (i.e., 0.2*6 µg Se/g dw)[3]. A bioaccumulation factor (BAF) for chinook salmon exposed to Se from both water and food simultaneously was not found in the literature. Hermanutz *et al.* (1992), however, reported a BAF of about 500[4] (based on wet weight of Se in the whole body) for bluegill exposed to selenium from water and food in an experimental stream environment. Given a safe tissue (whole body) level of 1.2 µg Se/g ww and BAF of 500, it was estimated that a concentration of 2.4 µg/L selenium in water would protect freshwater life from selenium toxicity due to its accumulation in tissue.

C. Sediment Concentration Approach

Selenium exhibits a strong association with particulate matter. Hence, the most prominent fate of dissolved Se in an aquatic environment is to bind and complex with particulate matter and settles out. The accumulation of Se in sediment followed by its movement into the food chain is the primary cause of Se toxicity in the aquatic environment. Hence, Canton and Van Derveer (1997) argued in favour of a sediment-based guideline for the protection of aquatic life and wildlife from selenium. Using data collected from streams of the middle Arkansas River basin in Colorado, Van Derveer and Canton (1997) showed that waterborne Se (W_{Se}-µg/L), sediment Se (S_{Se}-µg/g dw), and total organic carbon in sediment (TOC-% of dry weight) were highly

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[3] The toxicity threshold of 6 µg/g dw on whole body weight basis was chosen for the argument presented in this section, because this number was based on a sound statistical procedure that includes not one but all available data from the literature collected at various locations.

[4] Using global data and on-step model, Adams *et al.* (1998) found that water selenium (WS – µg/L) was correlated with mean egg selenium (MES – mg/kg dry weight) as follows: log (MES) = 3.366+0.561*log (WS). By expressing WS in the units of mg/L, the relationship in its curvilinear form can be written as: MES (mg/kg dw) = 48.2 [WS (mg/L)]$^{0.561}$. Further manipulation will yield the following relation:

MES(mg/kg dw) / WS (mg/L) = 48.2 WS$^{-0.439}$. This relation suggests that Se bioaccumulation (i.e., ratio MES/WS) in eggs is a function of it concentration in water. At a water concentration of 0.001 mg Se/L, this relation will yield a bioaccumulation factor of about 1000 on dry weight basis or 400 on wet weight basis (considering 80% moisure content). These BAFs are close to 500 used in this section.

correlated. The final form of the model, validated with data from other regions, is shown below:

$$\text{Ln } S_{Se} = \text{Ln}(W_{Se} * \text{TOC}) * 0.657 - 0.877 \qquad (1)$$

From the literature data, Van Derveer and Canton also noted that the 10th percentile of sediment Se associated with predicted adverse effects is 2.5 µg/g dw. This is only slightly above the 2 µg/g dw upper limit reported for uncontaminated sediment and soil. The following table was created from the above relationship, assuming that 2 µg Se/g in sediment would protect aquatic life from adverse effect of Se bioaccumulation in the food chain.

Safe Se in sediment (S_{Se})	Sediment TOC	Safe Se in water (W_{Se})
-µg/g dw-	-%-	-µg/L-
2	0.5	21.8
2	1.0	10.9
2	2.0	5.5
2	5.0	2.2

The above table suggests that the safe level for Se in water varies with the total organic carbon content of the sediment. In a lake with an average TOC concentration of 5%, aquatic life would be protected if selenium in the water were at or below 2 µg/L.

9.7.2 Marine Aquatic Life

The proposed guideline was determined using the chronic LOEL of 0.01 mg Se/L and a safety factor of 5 as in the case of freshwater life.

Wheeler *et al.* (1982) reported a 23-35% decrease in the growth of a red alga (*Porphyridium cruentum*) exposed to 0.01 mg/L selenate-Se over a 14-day period in test marine water containing sulphate comparable to that normally found in seawater (850 mg/L sulphate). A lower decrease (12%) in growth was also observed in a green alga (*Chlorella sp.*) exposed to 0.01 mg/L selenite-Se in test water with similar characteristics.

Glickstein (1978) reported that a selenium concentration of 0.01 mg/L increased abnormalities in the Pacific oyster (*C. gigas*) from 9.3% in the control to 12.9%. However, Glickstein's study produced inconsistent results with respect to the dose-response relationship and the ecological significance of the effect (i.e., abnormal development) could not be ascertained from the data.

The interim guideline for sediment and tissue for the freshwater environment (Section 9.7.1) were accepted as interim guidelines for the marine environment. There were not sufficient data for the marine environment to conduct an analysis such as in Section 9.7.1. However, there is some evidence in the literature in support of this argument. For instance, in modeling Se bioavailability to a benthic bivalve from particulate and solute pathway, Luoma *et al.* (1992) suggested that *Macoma balthica* ingesting sediment with >1.5 µg/g dw of selenium in the San Francisco Bay could achieve steady state tissue burdens approaching the level toxic to fish.

9.8 Application of the Aquatic Life Guidelines

As can be seen above, selenium toxicity in aquatic environments will depend on many factors, including its interaction with other elements. Although selenium has been shown to bioaccumulate, the potential for its bioaccumulation through food in the aquatic environments may also vary with several factors (lotic versus lentic environments). For instance, McDonald and Strosher (1998) found that in a fast-flowing river system (lotic environment) Se levels in sediments, algae, insects, and fish tissue increased modestly (2-5 times) despite 100 to 200 fold increase in waterborne selenium below a coal mine. Situations have also be found where fish in certain (e.g., lotic) environments may survive Se levels that have been found to be toxic to fish elsewhere (e.g., lentic environments – Lemly 1993), suggesting higher tolerance to naturally occurring Se (McDonald and Strosher 1998, Kennedy *et. al.* 2000).

Obviously, in such environments, there is a need to develop site-specific water quality objectives to account for both background water quality conditions and effect concentrations in the local. However, in a watershed, both lotic (fast-flowing water) and lentic (still or slow-moving water) can exist simultaneously. A site-specific water quality guideline protective of the most sensitive environment should be more appropriate in such situations.

10 Wildlife

10.1 Toxic Effects

The toxicity data for wildlife are summarized in Table 10.01. Studies conducted in the Kesterson Reservoir by Ohlendorf *et al.* (1986a and 1988) revealed that water entering the Kesterson ponds, from the contaminated San Luis Drain, had average levels of 0.3 mg Se/L. The concentration of selenium in plants, invertebrates and fish collected from the ponds ranged from 22-175 µg Se/g. The analysis of wildlife inhabiting the area revealed 16.7% dead embryos in the nests of mallards (*Anas platyrhynchos*) and 59.3% dead embryos in the nest of American coots (*Fulica american*). The authors also noted that no nests were found in 1984 to 1985 in an area where 92 nests had been found in 1983.

Fairbrother and Fowles (1990) reported that 3.5 mg/L selenite-Se in the drinking water of mallards did not affect immune function, but it increased the serum alanine amino-transferase (ALT - indicative of renal or to a lesser degree hepatic dysfunction in birds) level. However, 2.2 mg Se/L as selenomethionine appeared to affect certain aspects of mallard immune response system, including a suppression in delayed type hypersensitivity (DTH), increased activity of serum ALT, and an increased plasma glutathione peroxidase (GPX) activity.

Peterson and Nebeker (1992) modeled thresholds for waterborne selenium toxicity to

aquatic birds and mammals. The model considered the duration of time the birds spent in the contaminated areas, the proportion of their diet comprised of foods from contaminated aquatic environments, trophic position, food ingestion rates (function of body mass), and energy demands associated with activities such as reproduction. The toxicity thresholds for the marsh wren (*Cistothorus palustris*), belted kingfisher (*Ceryle alcyon*), osprey (*Pandion haliaetus*), bald eagle (*Haliaeetus leucocephalus*) and the mallard were estimated to be 0.8, 0.9, 1.3, 1.9, and 2.1 µg/L dissolved selenium, respectively. The toxicity thresholds for mammals in the same environment were 0.9 µg Se/L for bats and shrews, 1.1 µg Se/L for mink, and 0.7 µg Se/L for river otters. Lemly and Smith (1987), DuBowy (1989), and Skorupa and Ohlendorf (1991) also suggested that waterborne selenium (dissolved) concentrations between about 1 and 3 µg/L were protective of aquatic birds.

Heinz *et al.* (1989) observed those mallard ducklings on control diets with no added selenium, but born to parents who were fed 8 to 10 µg/g selenomethionine-Se (dry-weight) in their diet, had a significantly reduced survival. Females fed control diets with no added selenium had an average of eight ducklings that lived to 6 days of age (at which time all ducklings were sacrificed) compared to females fed 8 µg/g of selenomethionine-Se, who had an average of 4.6 young. There were no young born to females fed 16 µg/g selenomethionine-Se. Also, diets containing 8 and 16 µg/g (dry-weight) Se as selenomethionine caused malformations in 6.8% and 67.9%, respectively, of unhatched eggs compared with 0.6% for controls. The authors concluded that the dietary threshold necessary to impair reproduction in mallards is between 4 and 8 mg/g (dry-weight) selenium as selenomethionine. These investigators also suggested that when eggs from a wild population contain ≥1 µg Se/g (wet-weight), reproductive impairment may be possible and should be evaluated in that population. At 5 µg Se/g (wet-weight) in eggs, reproductive impairment is much more likely to occur.

Heinz and Fitzgerald (1993a) reported 25% mortality in mallards exposed to 20 µg Se/g (dry-weight) as selenomethionine for 16 weeks and 95% mortality at twice the concentration. These investigators also observed that, after one week of exposure, the 20 µg Se/g treatment compared to the control or the 10 µg Se/g treatment significantly depressed the body weight of the birds. However, four weeks after being returned to an untreated diet, the body weight of birds fed 20 µg Se/g had increased to the point of being statistically inseparable from the weight of the control birds. Finally, the concentrations of selenium in their blood were related to dietary selenium, but mortality was not clearly related to a threshold concentration of selenium in blood.

Heinz *et al.* (1987) compared the toxic effects of selenomethionine and selenite-Se at 10 µg/g (dry-weight) in mallards. Whereas selenite caused mainly embryotoxic effects, selenomethionine was mostly teratogenic, causing hydrocephaly, bill defects, eye defects, and foot and toe defects. They also noted that males accumulated more selenium because females can eliminate some in their eggs. Heinz (1993) exposed adult male mallards to a diet of 15 µg Se/g, as seleno-DL-methionine, for 21 weeks. After this initial exposure, the mallards were fed untreated food for 12 weeks and then were re-exposed to the selenium at 100 µg/g of diet for five weeks. The author observed that the earlier (i.e., 15 µg Se/g) exposure of mallards to selenium had no effect on the birds' response to the later (i.e., 100 µg Se/g) treatment. It was concluded that one should be concerned primarily about the current exposures of birds to selenium and not the previous exposures.

Raptors may be exposed to excessive selenium from contaminated prey. Wiemeyer and Hoffman (1996) exposed captive eastern screech owls (*Otus asio*) to diets containing 0 (control), 4.4, and 13.2 mg/kg (wet-weight) added selenium as seleno-DL-methionine. Adult mass at sacrifice and reproductive success of birds receiving 13.2 mg Se/kg were significantly depressed compared to the controls. Parents fed 4.4 mg Se/kg produced no malformed nestling, but the femur lengths of the young were shorter than those of the controls. Also, the 5-day-old nestling from parents fed 4.4 mg Se/kg indicated oxidative stress in the liver (indicator for the onset of Se-related toxicosis), including a 19% increase in glutathione peroxidase activity, a 43% increase in the ratio of oxidized glutathione to reduced glutathione, and a 17% increase in lipid peroxidation.

Selenomethionine is a major form of selenium in some plant material such as wheat seeds and soybeans. In nature, selenomethionine is found almost exclusively in the 'L' form, which is one the two stereoisomer forms it can take. The other stereoisomer, the 'D' form, is found in equal amounts in manufactured selenomethionine (Heinz and Hoffman 1996). In comparing the toxicity of various forms of selenium on reproduction of mallards, Heinz and Hoffman (1996) reported that seleno-DL-methionine and seleno-L-methionine were equally toxic; however, both were more toxic than selenium from selenized yeast. Also, regardless of the source, a diet of 10 mg Se/kg (dry-weight) posed a serious threat to the reproductive success of mallards.

In their assessment of Se transfer in the food chain to avian wildlife species at 15 sites, Adams *et al.* (1998), Skorupa and Ohlendorf (1991) and Ohlendorf *et al.* (1993) reported a strong correlation between water and mean egg Se (or MES) concentrations. Adams *et al.* (1998) used global data and suggested that a concentration of 6.8 µg/L selenium in water was associated with a threshold concentration of 20 µg/g dw in eggs (MES) for reproductive effects in birds. They also concluded that the proposed concentration of 6.8 µg Se/L would protect 90% of the sites and species from the adverse effects of selenium. The threshold MES of 20 µg/g dw in eggs from Adams *et al.* (1998), was higher than the contamination threshold concentrations[3] of 3 µg/g dw in eggs from Skorupa and Ohlendorf (1991) and 8 µg/g dw in eggs (impaired egg hatchability) from Ohlendorf and Sontolo (1994). This difference in the threshold concentrations can be attributed to different endpoints chosen to be protected and the models used by the investigators. In a recent publication, based on data published in the literature, Fairbrother *et al.* (1999) reported an EC_{10} of 16 µg/g dw in eggs (MES) and an EC_{50} of 21 µg/g dw in eggs (MES), using the most sensitive endpoint of chick mortality. Again, this differs from the threshold of 6 µg/g dw in eggs proposed by Skroupa (1998).

10.2 Summary of Existing Guidelines

Water quality guidelines for the protection of wildlife (excluding aquatic life) were not found in the literature.

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[3] Contamination threshold refers to concentration that may be found in naturally occurring selenium environments. It is also called as 'natural background index'.

10.3 Recommended Guidelines

To protect wildlife it is recommended that the maximum concentration of total selenium should not exceed 0.004 mg Se/L.

Selenium in eggs is the prime indicator of its toxicity to avian species. It is recommended that a concentration of 1.4 mg Se/kg wet weight in eggs (i.e., 7 mg Se/kg dry weight[6], assuming 80% moisture content) be used as an alert level. When average concentration of selenium in avian eggs approaches this level, a detailed site-specific investigations should be undertaken to assess the effects of selenium in the environment.

10.4 Rationale

The proposed guideline was based on the toxicity thresholds of birds exposed to selenium in water and food in aquatic systems. Using global data, Adams *et al.* (1998) determined that 0.0068 mg Se/L will protect 90% of avian species exposed to selenium. This corresponds to an average concentration of 0.020 mg/g selenium (dry weight) in the eggs of the avian species. This concentration is slightly greater that the threshold concentration (EC_{10}) of 0.016 mg/g dw in eggs reported by the same group of investigators (Fairbrother *et al.* 1999). Bird eggs from selenium-normal environments rarely average greater than 0.003 mg/g dw (mean egg selenium or MES) (Skorupa and Ohlendorf 1991). Using the Skorupa and Ohlendorf (1991) model relating mean egg Se and water Se concentrations, Adams *et al.* (1998) determined that an upper 95% confidence limit of 0.0023 mg Se/L in water will correspond to 0.003 mg/g dw MES. The proposed guideline of 0.004 mg Se/L to protect avian wildlife from the adverse effects of selenium is an average of the two values (0.0023 and 0.0068 mg Se/L).

Peterson and Nebeker (1992) modeled a threshold of about 0.001 mg/L in water for birds and mammals that bioaccumulate selenium by feeding on contaminated aquatic life. Peterson and Nebeker's data were not accepted for the guideline derivation purposes, since the assumptions used in the model could not be verified. For instance, it was assumed that selenium accumulates in wildlife foods in a general and predictable manner, and that wildlife consumes only contaminated foods. Because of the uniform treatment (i.e., assumptions used) of all wildlife in their model, we accepted their proposition that the protective concentration for all wildlife (birds and mammals) was similar in magnitude.

11 Irrigation

The effects of selenium on agricultural crops are summarized in Table 11.01.

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[6] Geometric mean of EC_{10} concentration of 16 µg Se/g dw in eggs (Fairbrother *et al.* 1999) and egg Se concentration of 3 µg/g in contaminated-free environment (Skorupa and Ohlendorf 1991).

11.1 Phytotoxicity

Plant species from the genera *Astragalus*, *Xylorhiza*, *Oonopsis*, and *Stanleyea* are capable of growing in seleniferous soils and accumulating high concentration of Se (Rosenfeld and Beath 1964). These plants, classified as Se accumulators, are considered to have an unpleasant odour associated with high concentrations of Se-containing organic compounds, and can be toxic to animals grazing on them.

Typical agricultural crops have a much lower tolerance to Se. The symptoms of Se toxicity include snow-white chlorosis of leaves and pink rot tissue in grasses, and general stunting, yellow chlorosis, and pink leaf veins in other plants. Apparently, the toxic effects of Se to plants are caused largely by interference with sulphur (S) metabolism. The small physical and chemical differences between Se and S result in significant biological differences within a plant. The similarity of Se-amino acids to their S-analogues of cysteine and methionine can disrupt the normal biochemical reactions and enzyme function within the cell. Selenium accumulator plants, however, have a mechanism that prevents Se incorporation into protein, thus avoiding Se-induced phytotoxicity (Mikkelsen *et al.* 1989).

Toxicity of naturally occurring Se to agricultural crops in the field has not been documented in the literature. Published values of tissue selenium concentrations associated with 10% yield reduction in the laboratory range from 19-94 mg Se/kg (selenate) and 12-30 mg Se/kg (selenite) for alfalfa, and 2-3 mg Se/kg (selenate) for rice, mustard, pea, and wheat plants (Mikkelsen *et al.* 1989). Tolerance to selenium depends upon plant and selenium species. In a review of published values, Mikkelsen *et al.* (1989) noted that the lowest concentrations of selenium in plant tissue, causing 10% reduction in yield, were 3 mg Se/kg (dry weight - mustard, pea, and wheat) for selenate and 10-15 mg Se/kg (dry weight - wheat) for selenite. The authors did not report the Se concentrations in the soils.

In a growth chamber study, Soltanpour and Workman (1980) reported that soils treated with selenite-Se and yielding 2 mg Se/kg dry weight (ammonium bicarbonate-DTPA extractable) were highly toxic to alfalfa. Jump and Sabey (1989) reported that the ammonium bicarbonate-DTPA extractable selenium in soil might range from 1% to 17% of the total selenium, depending on the soil type. Singh and Singh (1978) studied selenium toxicity to nonaccumulator plants in a greenhouse. They reported wheat-grain production of 100%, 72%, 17%, and 11%, respectively, in soils treated with 0, 2.5, 5, and 10 mg Se/kg as selenite. The grain contained 0.6, 10.2, 24.5, and 36.8 mg Se/kg dry weight, respectively.

Broyer *et al.* (1966) found that 0.025 mg Se/L in a nutrient solution decreased the yield of alfalfa. Mild toxicity was displayed in bush beans at 8 mg Se/L, as Na_2SeO_3, in solution culture (Wallace *et al.* 1980). In sand cultures, Davis *et al.* (1978) found that the critical levels of selenite-Se causing toxicity to young barley plants were 5 mg/L (in solution) and 30 mg/kg dry-weight (in tissue). In the literature, a selenate-Se concentration as low as 0.1 mg/L, in solution cultures void of sulphate, was reported to produce detectable injury to wheat plants, but this was probably due to sulphur deficiency, since signs of injury did not occur in the presence of sulphur (Adriano 1986). More recently, Mikkelsen *et al.* (1988) reported that the growth of alfalfa, in

sand cultures, decreased when exposed to a solution containing 0.25 mg/L selenate-Se.

11.2 Uptake by Plants

All plants are capable of taking up Se from soils. While Se is an important element in animal nutrition, the evidence that Se is essential to plants is not convincing. However, there are plant genera, called 'indicator, or 'accumulator' plants, where Se may be required for normal growth (Adriano 1986).

The Se-accumulating plants have been divided arbitrarily into three groups, depending upon their ability to accumulate selenium: (1) 'Primary Se-Accumulator, or Indicator, Plants' are believed to require Se for growth and may accumulate large amounts (often several thousand mg/kg), but levels <100 mg Se/kg are common. These plants are good indicators of seleniferous soils and include species from the genera *Astragalus*, *Machaeranthera*, *Happlopappus*, and *Stanleya*; (2) 'Secondary Se Absorbers' do not require Se for growth and rarely contain more than a few hundred mg Se/kg tissue, although lesser amounts are common. They may be found in species of *Atriplex*, *Aster*, *Gutierrezia*, *Catelleja*, *Grindelia*, *Machaeranthera*, and *Mentzelia*; (3) 'Grasses, Small Grains, and Other Shallow-Rooted Plants' usually accumulate toxic amounts of Se ranging from 5 to 12 mg/kg, but seldom more than 50 mg/kg. The Se accumulation is dependent on factors other than genera, species, and availability of soil Se. Some plants such as white clover (*Trifolium repens* L.), buffalograss (*Buchloe dactyloides*), and gamma grass (*Bouteloua* spp.) take up very little Se, even when growing on seleniferous soil. Other plants, such as those belonging to the *Crucifera* family (certain mustards, cabbage, broccoli, and cauliflower), may concentrate relatively high levels of Se if grown on high-Se soils (James *et al.* 1989).

The mobility and availability of selenium in soils depend upon several factors, including plant characteristics (e.g., species, age), soil characteristics (e.g., pH, texture and mineralogy, and organic matter content), presence of competitive ions such as sulphate and phosphate, and Se species (selenite, selenate, etc.) and concentration in soils (Adriano 1986). As a result, the concentration of Se in any one crop may vary widely. In general, however, the root and bulb crops contain the highest concentration of Se (mean = 0.407 mg Se/kg dry-weight) followed by field crops (mean = 0.279 mg Se/kg dry-weight), leafy vegetables (mean = 0.110 mg Se/kg dry weight), seed vegetables (mean = 0.066 mg Se/kg dry weight), vegetable fruits (mean = 0.054 mg Se/kg dry weight), and tree fruits (mean = 0.407 mg Se/kg dry weight) (Mikkelsen *et al.* 1989).

Soil pH influences plant Se uptake by altering the oxidation state of Se in soils and the capacity of clays and ferric oxide to adsorb Se. In general, plants accumulate more Se at higher pH (Mikkelsen *et al.* 1989). Hamdy and Gissel-Nielsen (1977) showed that clays and ferric oxide quickly remove Se^{+4} from soil solution, thus making Se less available to plants. They also found that 1:1 clays (e.g., kaolinite) had a greater Se^{+4} fixation capacity than 2:1 clays. Among the 2:1 clays minerals, vermiculite had a greater Se^{+4} adsorption capacity than montmorillonite, but Fe_2O_3 adsorbed more Se^{+4} than all the minerals tested. Reports concerning the effect of soil

organic matter on the uptake of Se by plants are mixed.

Westerman and Robbins (1974) reported that the addition of gypsum to soils reduced significantly the Se concentration in alfalfa. Since sulphur (in gypsum) also increased the yield of alfalfa, this reduction was attributed to a dilution effect; i.e., although the tissue-Se concentration decreased, the total uptake of Se by the crop increased. Reduction in the Se uptake by red clover and perennial ryegrass, from soils naturally high in selenite-Se, was also reported in response to ammonium sulphate treatment (Williams and Thornton 1972). Mikkelsen *et al.* (1988) reported a negative correlation between tissue Se concentration and sulphate level in irrigation water for alfalfa grown in sand cultures. However, the interaction between Se and sulphur was not observed in soils low in sulphur and Se (Spencer 1982) or soils producing vegetation with inadequate Se for animal nutrition (Gupta and Winter 1975). From these data, Mikkelsen *et al.* (1989) concluded that the presence of SO_4^{2-} in soil generally reduces the concentration of plant Se either through antagonism or may simply reflect a dilution of plant Se due to increased growth.

In a field experiment, Cary and Allaway (1973) applied 0, 2.2, and 4.5 kg selenite-Se/ha to five silt loam soils cropped with corn, oat, or various forage crops for four years. They reported that a single application of 2.2 kg Se/ha was sufficient to raise plant Se concentrations to levels sufficient to protect animals from Se deficiency for at least 4 years on perennial pasture and two to three years on corn. Application of 4.5 kg Se/ha further raised tissue Se concentrations, but did not produce vegetation with Se levels potentially harmful to animals. Gupta *et al.* (1982) reported that annual application of small amounts of selenite-Se were more effective than a single, large application for annual crops. They also reported that the residual effect of selenite-Se application to soil may be lost for barley following a single cropping season, whereas, for perennial pasture, a single application was found to have a residual effect of increasing plant Se concentrations for four to five years.

In a more recent field trials, Banuelos *et al.* (1992) reported that the first clipping (after 60 days) of the plant species, grown in soils containing 0.7 mg Se/kg dry weight, accumulated selenium to the levels of 1.3 mg Se/kg dry matter in tall fescue (whole plant), 4.7 mg Se/kg dry matter in alfalfa (whole plant), 3.1 mg Se/kg dry matter in birdsfoot trefoil (whole plant), 34.1 mg Se/kg dry matter in wild mustard (whole plant), and 51 mg Se/kg dry matter in canola (leaves). In a review of the literature, these investigators also noted that the desirable Se level (or safe level for consumption by animals) in cereals and forages is between 0.05 and 2 mg Se/kg dry matter. Obviously, a concentration of 0.7 mg/kg selenium in soil may be excessive for some crops (e.g., wild mustard and canola), producing feed that is not safe for animals. Gupta and Winter (1981) reported that a selenium salt rate of 1 to 2 kg/ha would enhance plant Se concentration sufficiently to meet the dietary requirements of cattle and not cause Se toxicity. Based on a soil density of 1300 kg/m^3 and a leaching depth of 0.15 m, these rates corresponded to soil concentrations of 0.5 to 1 mg Se/kg.

Gissel-Nielsen and Bisbjerg (1970) tested the uptake of elemental Se, selenite-Se, and selenate-Se from soils by red clover, alfalfa, mustard, and sugar beets. Except for mustard, elemental Se uptake was very little. Selenite-Se uptake was roughly proportional to its soil concentration, regardless of the solubility of the salt added. However, the uptake of Se by plants

from soils treated with selenate-Se salts was 20 to 50 times more than for the selenite-Se salts treatment. During the two-year field experiment, they found that mustard recovered 0.01% of elemental Se, 4% of K_2SeO_3, and 30% of the K_2SeO_4 applied to the soil. Carlson *et al.* (1991) have confirmed the greater availability to plants of selenate than selenite, which probably reflects the tendency of selenite to become adsorbed on soil clays and hydrous oxides.

The atmosphere plays an important role in the biochemical cycle of Se, which may also affect concentrations in vegetation. In a study of plant and environment interactions, Haygarth *et al.* (1995) reported that both atmospheric and soil Se was accumulated in ryegrass. The percent contribution of Se in the pasture leaves from the soil was 47% (pH 6.0) and 70% (pH 7.0), with by inference, the remainder coming from the atmosphere.

11.3 Summary of Existing Guidelines

The CCREM (1987) recommended that the concentration of total selenium in irrigation waters should not exceed 0.02 mg Se/L for continuous use on all soils, and 0.05 mg Se/L for intermittent use on all soils. USEPA (1973) recommended a maximum concentration of 0.02 mg Se/L in irrigation water for continuous on all soils. Ontario (OMOE 1984) also recommended 0.02 mg Se/L and Manitoba (Williamson 1988) recommended 0.05 mg Se/L for field crops and 0.02 mg Se/L for greenhouse crops.

11.4 Recommended Water Quality Guidelines

It is recommended that the concentration of total selenium in irrigation water supplies should not exceed 0.01 mg/L.

11.5 Rationale

Two procedures were used to derive the guideline for irrigation water supplies:

1. The lowest observed effect concentration (LOEC) in soil causing 28% reduction in yield was reported to be 2.5 mg Se/kg dry-weight (Singh and Singh 1978). Using the CCME protocol (1993), the no observed effect concentration (NOEC) was estimated to be (2.5 ÷ 4.5) or 0.56 mg Se/kg. Based on the literature LOEC, the estimated NOEC, and the uncertainty factor of 10, the acceptable soil concentration (ASC) was computed as follows:

$$ASC = (2.5 \text{ mg Se/kg} \times 0.56 \text{ mg Se/kg})^{0.5} \div 10 = 0.12 \text{ mg Se/kg}$$

Assuming a soil bulk density of 1300 kg/m^3 and a leaching depth of 0.15 m, the allowable contaminant mass (ACM) was calculated as follows:

$$ACM = ASC \text{ (mg Se/kg)} \times 1\,300 \text{ kg/m}^3 \times (100 \text{ m} \times 100 \text{ m} \times 0.15 \text{ m})/\text{ha}$$

$$ACM = 0.12 \times 1\,300 \times 100 \times 100 \times 0.15 = 234\,000 \text{ mg Se/ha (or 0.234 mg/ha)}$$

The allowable contaminant mass thus calculated is about three times lower than 0.7 mg Se/kg soil treatment that raised the selenium level in wild mustard and canola above the acceptable level for animal consumption (Banuelos *et al.* 1992). Also, the computed ACM appears to be in line with the Cary and Allway (1973) recommendation (if expressed on an annual basis) that soils treated at the rate of 2.2 kg Se/ha will raise Se levels in plants sufficient to protect animals from selenium deficiency for at least four years on perennial pastures.

Assuming an annual irrigation rate (IR) of 1.2×10^7 L/ha, the species maximum acceptable toxicant concentration (SMATC), or the recommended water quality guideline was calculated as follows:

$$SMATC = (ACM \div IR) = 234\,000 \text{ mg/ha} \div 1.2 \times 10^7 \text{ l/ha} = 0.0195 \text{ mg/L}$$

$$SMATC \approx 0.02 \text{ mg/L}$$

2. Mikkelsen *et al.* (1988) reported that the lowest observed effect concentration (LOEC) of 0.25 mg Se/L caused a 19.5 to 25% reduction in the yield of alfalfa grown in a greenhouse sand culture. The no observed effect concentration (NOEC) was estimated to be $0.25 \div 4.5 = 0.056$ mg Se/L, in accordance with the procedure suggested in the CCME (1993) protocol. Assuming an uncertainty factor (UF) of 10, the species maximum acceptable concentration (SMATC) was calculated as follows:

$$SMATC = (LOEC \times NOEC)^{0.5} \div UF = (0.25 \times 0.056)^{0.5} \div 10 \approx 0.010 \text{ mg Se/L.}$$

It is recommended that the lowest (0.01 mg Se/L) of the two values computed above be accepted as the water quality guideline.

The selenium guideline may be influenced by factors such as availability of selenium, form of selenium, and sulphate content of irrigation water. For instance, Albasel *et al.* (1989) proposed a guideline of 0.1 mg Se/L in irrigation waters for the west side of the San Joaquin Valley in California. The specific conditions that justified this guideline were as follows: (i) Se in the drainage water of the valley was largely in the selenate form, which is not appreciably adsorbed by soils and is thus readily leached from the root zone; (ii) the waters containing high concentrations of Se also had substantial quantities of sulphate that dramatically reduced selenate-Se adsorption by plants, and (iii) the high salinity of the valley water demanded a high leaching fraction of irrigation water, which caused a fraction of the Se applied in irrigation water to leach through the root zone. These factors were not considered in this document because their quantitative relationships with Se toxicity/uptake could not be established from the published literature.

12 Livestock Watering

12.1 Toxic Effects

There are three basic types of selenium poisoning in livestock:

(a) acute poisoning that results from consumption (usually in a single feeding) of a sufficient quantity of highly seleniferous weeds,

(b) chronic poisoning or 'blind staggers' from consumption of moderately toxic amounts of seleniferous weeds over an extended period of time, and

(c) chronic poisoning or 'alkali disease' caused by the consumption of moderately seleniferous grains and forage grasses over a period of several weeks to months (Eisler 1985). The distinction between the two types of chronic poisoning is described as follows: alkali disease in cattle, horses, hogs, and poultry is said to be associated with the consumption of seleniferous forages in which Se is bound to protein (i.e., water-insoluble Se). In comparison, blind staggers that occur in cattle, and possibly sheep, is associated with the consumption of Se-indicator plants over a period of time wherein the Se is in a water-soluble form (Rosenfeld and Beath 1964).

Alkali disease has been experimentally reproduced using both inorganic Se compounds and seleniferous plants and seems to be the principal manifestation of Se poisoning. On the other hand, selenium-induced blind staggers has not been reproduced by using inorganic Se compounds and is questionable when using seleniferous plants. Therefore, it seems to be a condition of questionable etiology in which Se may or may not be involved (James *et al.* 1989).

The most characteristic sign of acute Se poisoning in animals is the development of the so-called 'garlicky breath odour', which is due to the pulmonary excretion of volatile selenium compounds (e.g., dimethyl selenide) by animals overexposed to selenium. Other signs of acute Se poisoning in domestic livestock include abnormal movements, lowered head, drooped ears, diarrhoea, elevated temperature, rapid pulse, laboured breathing, bloating with abdominal pain, increased urination, and dilated pupils. Before death, which is due to respiratory failure, there is complete prostration and lethargy (Eisler 1985, WHO 1987).

Stowe and Herdt (1992) reported selenium toxicity in pigs and horses exposed to a diet of 8.1 mg/kg dry weight for a period of 5 weeks (pigs) and 20 mg/kg dry weight for ≥3 weeks (horses). Assuming that large animals consume 2-3% of food/day of their body weight, these toxic doses were expressed as 0.16-0.24 mg Se/kg body weight/d for pigs and 0.4-0.6 mg Se/kg body weight/d for horses. The maximum dietary tolerable level of 2 mg Se/kg dry-weight for livestock was recommended by NAS (1980).

MacDonald *et al.* (1981) reported that a single dose of 2 mg Se/kg body weight administered to neonatal calves resulted in lassitude, inappetance, dyspnea and death within 12 hours following injection. Smyth *et al.* (1990) reported that two of four sheep (12-week-old lambs) died within 16 hours of administration of 5 mg Se/kg body weight as sodium selenite. In another study, 2 mg Se/kg body weight produced 100% mortality in swine within 4 hours of

injection. A lower dose of 1.2 mg Se/kg body weight produced 100% mortality in 5 days (Orstadins 1960).

Smyth *et al.* (1990) reported that a single oral dose of 5 mg Se/kg body weight/d caused edema in the skeletal muscles of the diaphragm and congestion of viscera in sheep. In a study of weaned 5-week-old pigs, a dose of 1.3 mg Se/kg body weight/d, as sodium selenite, killed all eight pigs within 10 days (Wilson *et al.* 1989). Pigs exposed to organic (in plants) or inorganic (sodium selenate) in the diet at the rate of 1.1 to 1.3 mg Se/kg/d exhibited diffuse swelling and vacuolar degeneration of hepatocytes, and had a mean survival of 44 days (Baker *et al.* 1989). However, pigs exposed to 0.47 mg Se/kg/d of sodium selenite in their feed for 35 days showed no liver damage (Mahan and Magee 1991). Mihailovic et al. (1992) reported hepatic effects in pigs exposed to 0.59 or 1.07 mg Se/kg/d, as sodium selenite, in feed for 8 weeks.

Harr and Muth (1972) reported a decreased conception rate and an increased fetal resorption rate in cattle, sheep, and horses fed natural diets containing 20-50 mg Se/kg diet. Assuming that large animals consume an amount of food equal to about 2-3% of their body weight/d, the dose would correspond to 0.5-1.5 mg Se/kg body weight/d. These levels of Se also produced other signs of toxicity including hair loss, lameness, and degenerative fibrosis of the heart, liver, and kidney.

12.2 Summary of Existing Guidelines

The CCME (CCREM 1987), recommended that the concentration of total selenium in water used for livestock watering should not exceed 0.05 mg/L. The Province of Manitoba (Williamson 1988) also recommended a maximum concentration of 0.05 mg Se/L for livestock watering. The recommended limits for livestock watering are 0.02 mg Se/L in Australia (Hart 1984), 0.05 mg Se/L in the United States (USEPA 1973), and 0.05 mg Se/L in Ontario (OMOE 1984).

12.3 Recommended Water Quality Guidelines

A water quality guideline of 0.03 mg/L selenium is recommended to protect livestock water use.

12.4 Rationale

Based upon the above review, it appears that pigs are among the most sensitive livestock species to selenium effects. Puls (1981) reported adequate[7] levels of selenium ranging from 0.2 to 0.8 mg Se/kg diet for pigs, with an average value of 0.5 mg Se/kg diet. Assuming an average daily dry-matter intake of 2.5% of the body weight, the safe dose, or the total daily intake (TDI),

[7] Adequate levels are defined as levels sufficient for full functioning of all body mechanisms with a small margin of reserve to counteract commonly encountered antagonistic conditions.

was determined to be 0.5 x 0.025 = 0.0125 mg Se/kg body weight/d. The safe dose thus determined is nearly the same as the 0.0085 mg Se/kg body weight/d calculated using the lowest adverse observed effect level (LOAEL) of 8.1 mg Se/kg diet (Stowe and Herdt 1992)[5] and the CCME protocol (1993).

Assuming an average body weight (BW) for a pig of 200 kg and a daily water intake rate (WIR) of 17 L/d (Warrington 1993), the reference concentration (RC) was calculated as follows:

$$RC = (TDI \times BW) \div WIR = 0.0125 \text{ mg Se/kg/d} \times 200 \text{ kg} \div 17 \text{ L/d} = 0.147 \text{ mg/L}$$

Assuming a drinking water contribution (PDWC) of 20% for the daily body burden of selenium for livestock, the recommended water quality guideline was determined to be:

$$\text{Guideline} = RC \times PDWC = 0.147 \text{ mg/L} \times 0.20 \approx 0.03 \text{ mg/L}.$$

13 Industrial Water Supplies

Evidence suggesting adverse effects of selenium on industrial water supplies was not available from the literature. Therefore, a water quality guideline for industrial water supplies is not recommended at this time.

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[5] Assuming an average dry-matter intake of 2.5% of body weight/day, the LOAEL, in terms of body weight, is equal to 0.203 mg Se/kg body weight/d. The no observed adverse effect level was estimated to be 0.203÷5.6 = 0.036 mg Se/kg body weight/d. Using an uncertainty factor (UF) of 10, the tolerable daily intake (TDI) was calculated to be $(0.203 \times 0.036)^{0.5} \div 10 = 0.0085$ mg Se/kg body weight/d.

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Table 5.01: Bioaccumulation and bioconcentration of selenium in freshwater aquatic orgamisms

Source	Chemical	Species	Bioaccumulation Factor (BAF) or Bioconcentration Factor (BCF) (in dry wt unless otherwise stated)
Ohlendorf, 1989	-	algae	* BCF = from 100 to 2600 under natural conditions
Kiffney and Knight, 1990	selenite	***Anabaena flos-aquae*** (cyanobacterium)	* 2-10 day exposure, BCF = 267 to 1004
Kiffney and Knight, 1990	selenate	***Anabaena flos-aquae*** (cyanobacterium)	* 2-10 day exposure, BCF = 30 to 115
Kiffney and Knight, 1990	seleno-methionine	***Anabaena flos-aquae*** (cyanobacterium)	* 2-10 day exposure, BCF = 1520 to 12,193
Peterson and Nebeker, 1992	selenite	aquatic plants (rooted macrophytes)	long term exposure, BAF = 1,200
Boisson *et al.*, 1995	selenite	***Cricosphaera elongata*** (Droop) Braarud (coccolithophores/unicellular marine algae)	14-d exposure, BCF = 102.7 to 363
Ohlendorf *et al.*, 1986(a)	-	filamentous algae	long term exposure, BCF = 117
Saiki *et a* l., 1993	-	filamentous algae	long term exposure, BCF = 118 to 2466
Besser *et al.*, 1989	selenate	Macrophytes	28 d exposure, BCF = 72
Besser *et al.*, 1989	selenite	Macrophytes	28 d exposure, BCF = 363
Besser *et al.*, 1989	seleno-methionine	Macrophytes	28-d exposure, BCF = 3,266
Besser *et al.*, 1989	selenate	Periphyton	28-d exposure, BCF = 141
Besser *et al.*, 1989	selenite	Periphyton	28-d exposure, BCF = 755
Besser *et al.*, 1989	seleno-methionine	Periphyton	28-d exposure, BCF = 16,836
Ohlendorf *et al.*, 1986(a)	-	rooted plants	long term exposure, BCF = 174

Source	Chemical	Species	Bioaccumulation Factor (BAF) or Bioconcentration Factor (BCF) (in dry wt unless otherwise stated)
Cumbie and VanHorn, 1978	-	plankton	long term exposure, BCF = 4,000 to 10,000
Besser *et al.*, 1989	selenate	Zooplankton	28-d exposure, BCF = 351
Besser *et al.*, 1989	selenite	Zooplankton	28-d exposure, BCF = 1,087
Besser *et al.*, 1989	seleno-methionine	Zooplankton	28-d exposure, BCF = 28,870
Peterson and Nebeker, 1992	selenite	aquatic insects (and other invertebrates)	long term exposure, BAF = 1,800
Ohlendorf *et al.*, 1986(b)	-	aquatic invertebrates	long term exposure, BCF = greater than 1000 (based on wet wt)
Saiki *et a* l., 1993	-	crayfish	long term exposure, BCF = 172 to 1733
Ingersoll et al., 1990	mixture of 6 : 1 selenate to selenite	***Daphnia ma* gna** (water flea)	*long term exposure, BCF range from 71 to 322 dependant on water concentration
Saiki *et a* l., 1993	-	invertebrates	long term exposure, BCF = 284 to 2967
Ohlendorf *et al.*, 1986(a)	-	small invertebrates	long term exposure, BCF = range from 74 to 583
Peterson and Nebeker, 1992	-	small fish (mosquitofish/planktivores)	long term exposure, BAF = 2,600
Ohlendorf *et al.*, 1986(b)	-	***Gambusia affinis*** (mosquitofish)	long term exposure, BCF = 100 (based on wet wt)
Saiki *et a* l., 1993	-	***Gambusia affinis*** (mosquitofish)	long term exposure, BCF = 200 to 5333
Saiki and Ogle, 1995	-	***Gambusia affinis*** (mosquitofish)	long term exposure, BCF = 310 to 3400
Ohlendorf, 1989	-	fish	*BCF = from 8 to 78 in laboratory and from 200 to 6000 in the field
Peterson and Nebeker, 1992	selenite	large fish (piscivores)	long term exposure, BAF = 6,800
Cleveland *et al.*, 1993	selenite	***Lepomis macrochirus*** (bluegill)	60-d exposure, BCF = 5-7

Source	Chemical	Species	Bioaccumulation Factor (BAF) or Bioconcentration Factor (BCF) (in dry wt unless otherwise stated)
Cleveland *et al.*, 1993	seleno-L methionine	***Lepomis macrochirus*** (bluegill)	90-d exposure, BCF = 0.5 - 1.0
Saiki *et a*l., 1993	-	***Lepomis macrochirus*** (bluegill)	long term exposure, BCF = 245 to 2133
Gillespie and Baumann, 1986	-	***Lepomis macrochirus*** (bluegills)	long term exposure, ovaries BCF = 451.5
Hermanutz *et al.*, 1992	selenite	***Lepomis macrochirus*** (bluegills)	40-wk exposure, liver BCF = 930 (wet wt measurements)
Hermanutz *et al.*, 1992	selenite	***Lepomis macrochirus*** (bluegills)	40-wk exposure, sleletal muscle BCF = 90 (wet wt measurements)
Saiki *et a*l., 1993	-	***Micropterus salmoides*** (largemouth bass)	long term exposure, BCF = 218 to 2266
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, whole body BCF = 6.97
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, gills BCF = 10.94
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, liver BCF = 8.25
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, intestine BCF = 16.89
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, kidney BCF = 11.83
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, brain BCF = 4.28
Chidambaram and Sastry, 1991	selenate	***Oreochromis mossambicus*** (Peters) (teleost fish)	50 d exposure, muscle BCF = 13.07
Ohlendorf *et al.*, 1988	-	aquatic birds	long term exposure, liver BAF = 314
Ohlendorf *et al.*, 1988	-	aquatic birds	long term exposure, kidney BAF = 322

Source	Chemical	Species	Bioaccumulation Factor (BAF) or Bioconcentration Factor (BCF) (in dry wt unless otherwise stated)
Fairbrother and Fowles, 1990	seleno-methionine	***Anas platyrhynchos*** (mallards)	12-wk exposure, muscle BCF = 10.45
Fairbrother and Fowles, 1990	seleno-methionine	***Anas platyrhynchos*** (mallards)	12-wk exposure, liver BCF = 6.82
KEY			
	* not known whether wet or dry wt used for calcul		

Table 9.01: Acute toxicity of selenium to freshwater fish

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Brachydanio rerio (zebrafish)	-	-	selenite	-	-	20.000	-	96-h LC50	Niimi and LaHam, 1976
	-	-	selenate	-	-	82.000	-	96-h LC50	Niimi and LaHam, 1975
Carassius auratus (goldfish)	-	F,M,1	selenite	157.0	-	26.100	-	96-h LC50	Cardwell *et al.*, 1976a,b
	-	-	selenite	-	-	110.000	-	12-h LC50	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	76.500	-	18-h LC50	
	-	-	selenite	-	-	71.300	-	24-h LC50	
	-	-	selenite	-	-	60.200	-	36-h LC50	
	-	-	selenite	-	-	46.500	-	48-h LC50	
	-	-	selenite	-	-	41.200	-	60-h LC50	
	-	-	selenite	-	-	36.600	-	96-h LC50	
	-	-	selenite	-	-	0.250	-	48-h, quantifiable change in activity including trained behavior; conditional avoidance	Weir and Hine, 1970
	-	-	selenite	-	-	36.600	-	96-h LC50	Davis *et a* l., 1988
Catostomus commersoni (white sucker)	-	-	-	-	-	48.600	-	48-h LC50	Duncan and Klaverkamp, 1983
	-	F,M,1	selenite	18.0	-	31.400	-	96-h LC50	
	-	F,M,1	selenite	29.0	-	29.000	-	LC50 or EC50 values	Klaverkamp *et al.*, 1983
Cyprinus carpio (common carp)	-	-	-	-	-	72.000	-	24-h LC50	Sato *et al.*, 1980
	-	R,U	selenite	-	-	35.000	-	96-h LC50	
	-	-	-	-	-	35.000	-	96-h LC50	Spehar *et al.*, 1982
Esox lucius (northern pike)	-	-	selenite	10.2	-	11.100	-	75-h LC50	Klaverkamp *et al.*, 1983

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Etroplus maculatus	8.2-8.3 cm	-	selenite	28.4	pH = 7.2; D.O = 6.0 mg/L; Temp. = 29.0°C; Alkalinity = 46.0 mg/L	10.700	-	96-h LC50, fish were lathargic, swimming with widely spread fins and were often found on the surface of the water-pinkish bellies were noted at time of death	Gaikwad, 1989
	-	-	-	-	-	7.620	-	96-h LC50	
Gambusia affinis (mosquitofish)	-	-	-	-	-	10.700 Se + 1.830 Cu + 0.670 Hg	-	96-h, 95 % mortality with mixture	
	-	S,U,2	selenite	45.7	-	12.600	-	96-h LC50	Reading, 1979
	-	-	-	-	-	>6.000	-	48-h LC50	Nassos *et al.*, 1980
Gambusia affinis (mosquitofish) (cont.)	-	-	selenite	-	-	76.000		96-h LC50	Davis *et a* l., 1988
Ictalurus punctatus (channel catfish)	juvenile	S,M,2	selenite	49.8	-	16.000	-	LC50 or EC50 values	Brooke *et al.*, 1985
	juvenile	S,M,2	selenate	51.0	-	66.000	-	LC50 or EC50 values	
	juvenile	S,U,2	selenite	41.0	-	4.110	-	LC50 or EC50 values	Mayer and Ellersieck, 1986
	-	F,M,1	selenite	157.0	-	13.600	-	96-h LC50	Cardwell *et al.*, 1976a,b
	-	-	selenite	-	-	46.700	-	23.04-h LC50	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	40.200	-	28.08-h LC50	
	-	-	selenite	-	-	24.900	-	52.08-h LC50	
	-	-	selenite	-	-	19.100	-	94.08-h LC50	
	-	-	selente	-	-	18.200	-	96-h LC50	Davis *et a* l., 1988
Jordanella floridae (flagfish)	-	F,M,1	selenite	157.0	-	6.500	-	96-h LC50	Cardwell *et al.*, 1976a,b
	-	-	selenite	-	-	44.300	-	44.4-h LC50, mortality	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	27.900	-	55.44-h LC50, mortality	
	-	-	selenite	-	-	16.900	-	67.2-h LC50, mortality	
	-	-	selenite	-	-	21.800	-	68.4-h LC50, mortality	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
	-	-	selenite	-	-	11.200	-	83.04-h LC50, mortality	
Jordanella floridae (flagfish)	-	-	selenite	-	-	9.300-33.200	-	24-h, measurable change in length and/or weight of test organism	
	-	-	selenite	-	-	9.300-33.200	-	24-h, ~mortality	
Lepomis macrochirus (bluegill)	juvenile	S,M,2	selenite	50.5	-	12.000	-	LC50 or EC50 values	Brooke *et al.*, 1985
	juvenile	S,M,2	selenate	50.4	-	63.000	-	LC50 or EC50 values	
	-	F,M,1	selenite	157.0	-	28.500	-	96-h LC50	Cardwell *et al.*, 1976a,b
	-	-	selenite	-	-	126.600	-	7.92-h LC50, mortality	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	82.100	-	18-h LC50, mortality	
	-	-	-	-	-	77.300	-	24-h LC50, mortality	
	-	-	selenite	-	-	40.000	-	96-h LC50	Davis *et al*., 1988
	-	-	-	-	-	0.005	-	48-h, change in ventilatory rate or breathing activity	Lemly, 1983
Micropterus salmoides (largemouth bass)	-	-	-	-	-	0.005	-	48-h, change in ventilatory rate or breathing activity	Lemly, 1983
Oncorhynchus kisutch (coho salmon)	swim up fry 8-12 weeks	S,M,2	selenite	211.0	pH = 7.82; Temp. = 12.0°C; Alkalinity = 87.2 mg/L	7.800	-	96-h LC50 freshwater study	Hamilton and Buhl, 1990
	advanced fry 15-21 weeks	S,M,2	selenite	333.0	pH = 7.79; Temp. = 12.0°C; Alkalinity = 36.6 mg/L	13.600	-	96-h LC50 brackish water study	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Oncorhynchus kisutch (coho salmon) (cont.)	swim up fry 8-12 weeks	S,M,2	selenate	211.0	pH = 7.82; Temp. = 12.0°C; Alkalinity = 87.2 mg/L	32.500	-	96-h LC50 freshwater study	Hamilton and Buhl, 1990 (cont.)
	advanced fry 15-21 weeks	S,M,2	selenate	333.0	pH = 7.79; Temp. = 12.0°C; Alkalinity = 36.6 mg/L	39.000	-	96-h LC50 brackish water study	
	-	-	selenate : selenite (3.5:1)	-	-	21.800	-	96-h LC50 freshwater study	
	-	-	selenate : selenite (6:1)	-	-	24.500	-	96-h LC50 freshwater study	
	-	-	selenate : selenite (14:1)	-	-	25.800	-	96-h LC50 freshwater study	
	-	-	selenate : selenite (4.2:1)	-	-	16.900	-	96-h LC50 freshwater study	
	-	-	selenate : selenite (3.5:1)	-	-	26.200	-	96-h LC50 brackish water study	
	-	-	selenate : selenite (6:1)	-	-	26.300	-	96-h LC50 brackish water study	
	-	-	selenate : selenite (14:1)	-	-	28.000	-	96-h LC50 brackish water study	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
(coho salmon)	-	-	selenate : selenite (4.2:1)	-	-	38.000	-	96-h LC50 brackish water study	
Oncorhynchus mykiss (rainbow trout)	-	-	-	-	-	8.100	-	96-h LC50	Spehar *et al.*, 1982
	-	-	-	-	-	12.500	-	96-h LC50	USEPA, 1980
	-	-	selenite	-	-	8.100	-	96-h LC50	Hodson *et al.*, 1980; Davis *et al.*, 1988
	-	-	selenite	135.0	-	7.200-8.800	-	96-h LC50	Hodson *et al.*, 1980
	-	-	-	-	-		>3.000	may be toxic to rainbow trout	Hilton *et al.*, 1980
	-	S,U,2	selenite	330.0	-	4.200-4.500	-	96-h LC50	Adams, 1976
	-	F,M,1	selenite	30.0	-	12.500	-	LC50 or EC50 values	Goettl and Davies, 1976a
	juvenile	S,M,2	selenate	51.0	-	24.000	-	LC50 or EC50 values	Brooke *et al.*, 1985
		F,M,1	selenate	45.0	-	47.000	-	LC50 or EC50 values	Spehar, 1986
Oncorhynchus mykiss (rainbow trout) (cont.)	-	S,M,1	selenite	40.0	pH = 7.2; Temp. = 12.0 °C	1.800	-	96-h LC50	Hunn *et al.*, 1987
Oncorhynchus tshawytscha (chinook salmon)	swim up fry 8-12 weeks	S,M,2	selenite	211.0	pH = 7.82; Temp. = 12.0°C; Alkalinity = 87.2 mg/L	13.800	-	96-h LC50 for freshwater study	Hamilton and Buhl, 1990
	advanced fry 15-21 weeks	S,M,2	selenite	333.0	pH = 7.79; Temp. = 12.0°C; Alkalinity = 36.6 mg/L	23.400	-	96-h LC50 brackish water study	
	0.31 g	S,M,2	selenite	-	-	100.000	-	24-h LC50	
	0.31 g	S,M,2	selenite	-	-	27.300	-	96-h LC50	
	0.46 g	S,M,2	selenite	-	-	65.800	-	24-h LC50	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
	0.46 g	S,M,2	selenite	-	-	13.100	-	96-h LC50	
Oncorhynchus tshawytscha (chinook salmon)	swim up fry 8-12 weeks	S,M,2	seleno-DL-methionine	211.0	pH = 7.82; Temp. = 12.0°C; Alkalinity = 87.2 mg/L	<21.600	-	96-h LC50 freshwater study	
	advanced fry 15-21 weeks	S,M,2	seleno-DL-methionine	333.0	pH = 7.79; Temp. = 12.0°C; Alkalinity = 36.6 mg/L	21.600	-	96-h brackish water study, no mortalities were seen in any conc. but at 21.6, 50% showed pronounced surfacing behaviour	
	-	S,M,2	selenate : selenite (1:3.2)	41.7	pH = 7.57; Alkalinity = 36.6 mg/L	13.900 selenite / 42.700 selenate	-	96-h LC50 soft water study	
	-	S,M,2	selenate : selenite : B (1:3.2:18)	41.7	pH = 7.57; Alkalinity = 36.6 mg/L	8.200 selenite / 26.200 selenate +146.000 B	-	96-h LC50 soft water study	
	-	S,M,2	selenate : selenite : B : Mo (1:3.2 :18:?)	41.7	pH = 7.57; Alkalinity = 36.6 mg/L	6.900 selenite / 22.500 selenite + 123.000 B & Mo	-	96-h LC50 soft water study	
	-	-	selenate : selenite (3.5:1)	-	-	46.600	-	96-h LC50 freshwater study	
	-	-	selenate : selenite (6:1)	-	-	50.900	-	96-h LC50 freshwater study	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Oncorhynchus tshawytscha (chinook salmon) (cont.)	-	-	selenate : selenite (14:1)	-	-	85.500	-	96-h LC50 freshwater study	Hamilton and Buhl, 1990 (cont.)
	-	-	selenate : selenite (4.2:1)	-	-	67.100	-	96-h LC50 freshwater study	
	-	-	selenate : selenite (3.5:1)	-	-	51.900	-	96-h LC50 brackish water study	
	-	-	selenate : selenite (6:1)	-	-	76.900	-	96-h LC50 brackish water study	
	-	-	selenate : selenite (14:1)	-	-	67.000	-	96-h LC50 brackish water study	
	-	-	selenate : selenite (4.2:1)	-	-	96.800	-	96-h LC50 brackish water study	
Oreochomis mossambicus **(Peters)** (teleost)	4.5 to 9.0 cm	S,M,1	selenate	-	-	16.365	-	48-h LC50 acute toxicity, from conc. tested ranging from 0-24 mg Se/L	Chidambaram and Sastry, 1991
	4.5 to 9.0 cm	S,M,1	selenate	-	-	11.572	-	96-h LC50 acute toxicity, from conc. tested ranging from 0-15 mg Se/L	
Perca flavescens (yellow perch)	-	F,M,1	selenite	10.2	-	11.700	-	LC50 or EC50 values	Klaverkamp *et al.*, 1983
Pimephales promelas (fathead minnow)	-	-	selenite	-	-	31.200	-	18.48-h LC50, mortality	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	27.900	-	21.6-h LC50, mortality	
	-	-	selenite	-	-	28.600	-	22.08-h LC50, mortality	
	-	-	selenite	-	-	24.300	-	24.48-h LC50, mortality	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
(fathead minnow)	-	-	selenite	-	-	19.500	-	30-h LC50, mortality	
	-	-	selenite	-	-	15.600	-	42-h LC50, mortality	
	-	-	selenite	-	-	10.900	-	72-h LC50, mortality	
	-	-	selenite	-	-	7.300	-	96-h LC50, mortality	
	-	-	selenite	-	-	2.900	-	96-h LC50, mortality	
	-	-	selenite	-	-	9.300-33.200	-	24-h, measurable change in length and/or weight of test organism	
	adult	S,U,2	selenite	292.0-323.0	Temp. = 13.0 - 25.0 °C	2.200-12.500	-	96-h LC50	Adams, 1976
	-	S,U,2	selenate	323.0	-	11.800	-	LC50 or EC50 values	
	-	S,U,2	selenate	323.0	-	11.000	-	LC50 or EC50 values	
	-	S,U,2	selenate	323.0	-	12.500	-	96-h LC50	
	30 d	S,M,2	selenite	51.1	-	1.700	-	LC50 or EC50 values	Brooke *et al.*, 1985
Pimephales promelas (fathead minnow) (cont.)	juvenile -	S,M,2	selenate	47.9	-	2.300	-	LC50 or EC50 values	Brooke *et al.*, 1985 (cont.)
	juvenile	S,U,2	selenite	40.0	-	7.760	-	LC50 or EC50 values	Mayer and Ellersieck, 1986
	fry	F,M,1	selenite	157.0	-	2.100	-	96-h LC50	Cardwell *et al.*, 1976a,b
	juvenile	F,M,1	selenite	157.0	-	5.200	-	96-h LC50	
	-	F,M,1	selenite	220.0	-	0.620	-	LC50 or EC50 values	Kimball Manuscript
	-	F,M,1	selenite	220.0	-	0.970	-	LC50 or EC50 values	
	-	F,M,1	selenate	46.0	-	5.500	-	LC50 or EC50 values	Spehar, 1986
	adult	-	-	-	-	0.620-0.970	-	96-h LC50	USEPA, 1980

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Pimephales promelas (fathead minnow) (cont.)	adult	-	selenite	329.0	pH = 7.3; D.O. = 5.3-6.2 mg/L; Temp. = 25.0°C; Alkalinity = 332.0 mg CaCO3/L	1.000	-	96-h LC50 (fed)	Halter *et* al., 1980
	-	-	selenite	-	-	40.000	-	96-h LC50	Davis *et a* l., 1988
	-	-	-	-	-	82.000	-	24-h LC50	Watenpaugh and Beitinger, 1985a
	-	-	-	-	-	22.200	-	24-h reduced thermal tolerance	Watenpaugh and Beitinger, 1985b
	-	-	-	-	-	1.100-7.300	-	96-h LC50	Adams, 1976
Salvelinus fontinalis (brook trout)	adult	F,M,1	selenite	157.0	-	10.200	-	96-h LC50	Cardwell *et al.*, 1976a,b
	-	-	-	-	-	87.300	-	6-h LC50	Caldwell *et al.*, 1976a
	-	-	-	-	-	70.300	-	6.96-h LC50	
	-	-	-	-	-	36.300	-	24-h LC50	
	-	-	-	-	-	23.800	-	48-h LC50	
	-	-	-	-	-	14.300	-	96-h LC50	
	-	S,M,1	selenite	40.0	pH = 7.2; Temp. = 12.0 °C	1.800	-	96-h LC50	Hunn *et al.*, 1987
Samotilus atromaculatus (creek chub)	-	-	selenite	-	-	12.000	-	48-h, mortality	Kim *et al.*, 1977

KEY

LC = Lethal Concentrat EC= Effective Concentration

S = Static Test Method

F = Flowthrough Test Method 1 = Primary

M = Measured 2 = Secondary

Table 9.02: Chronic toxicity of selenium to freshwater fish

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Brachydanio rerio (zebrafish)	-	-	selenite	-	-	3.000	-	7-d, mortality	Niimi and LaHam, 1975
	-	-	selenite	-	-	1.000	-	10-d, mortality	
	-	-	selenite	-	-	10.000	-	10-d, change in % hatch or time to hatch	
Carassius auratus (goldfish)	-	-	selenite	-	-	32.700	-	5-d LC50, mortality	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	22.300	-	6-d LC50, mortality	
	-	-	selenite	-	-	17.200	-	7-d LC50, mortality	
	-	-	selenite	-	-	13.000	-	9-d LC50, mortality	
	-	-	selenite	-	-	11.500	-	11-d LC50, mortality	
	-	-	selenite	-	-	8.800	-	14-d LC50, mortality	
	-	-	selenite	-	-	12.000	-	7 and 9-d LC50, mortality	Weir and Hine, 1970
	-	-	selenite	157.0	-	6.300	-	14-d LC50, mortality	Cardwell *et al.*, 1976a,b
	-	-	selenite	-	-	5.000	-	10-d, mortality	Ellis, 1937; Ellis *et al.*, 1937
	-	-	selenite	-	-	2.000	-	46-d, gradual anorexia and mortality	Ellis *et a* l., 1937
	-	-	selenate	175.0	-	8.780	-	7-d EC50, death and deformity	Birge, 1978
Ctenopharyngodon idella (grass carp)	adult	F,M,1	selenate / selenite (60:40 ratio)	-	pH = 7.5-11.0	0.025	-	~ 500-d study, mortality: none recorded alive (1 found dead and 3 unaccounted for, out of 4)	Crane *et a* l., 1992

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (ug/g) dry wt	Effect	Reference
Dorosoma petenense (threadfin shad)	all life stages	F,M,1	-	-	Temp. = 20.0-38.0 •C	0.010	and 15.000-70.000 in diet	2 yr study, mortality and deformity of fry, juveniles and adults; significant decrease in standing crop	Cumbie and Van Horn, 1978
Gambusia affinis (western mosquitofish)	-	F,M,1	-	-	-	.340-.390	-	long term study (1984), (compared to control) mean survival of fry was 70%; shorter length and earlier stage of development in stillborn fry than in live fry	Saiki and Ogle, 1995; BOR, 1987
	-	F,M,1	-	-	-	.340-.350	-	long term study (1985), (compared to control) mean survival of fry was 77%; shorter length and earlier stage of development in stillborn fry than in live fry; whole body conc. of in dry wt of fish is 100 ug/g	
Ictalurus platycephalus (flat bullhead)	all life stages	F,M,1	-	-	Temp. = 20.0-38.0 •C	0.010	and 15.000-70.000 in diet	2 yr study, mortality and deformity of fry, juveniles and adults; significant decrease in standing crop	Cumbie and Van Horn, 1978
Lepomis cyanellus (green sunfish)	all life stages	F,M,1	-	-	Temp. = 20.0-38.0 •C	0.010	and 15.000-70.000 in diet	2 yr study, mortality and deformity of fry, juveniles and adults; significant decrease in standing crop; complete reproduction failure	Cumbie and Van Horn, 1978

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Lepomis macrochirus (bluegills)	adult fish, eggs, and 30 day old fry	F, M, 1	Na2Se04/ Na2Se03 (6:1 ratio) + diet (seleno-L-methionine)	-	-	0.010	and in diet 4.600-33.300	11 wk study, during spawning, monitoring fry for 30 days after hatch, revealed that fry were significantly affected, especially of those whose parents had a combination with high diet Se (33.3 ug Se/g)	Coyle *et a* l., 1993
	adult	F, M,1	selenite	179.0	pH = 8.0; D.O. = 3.6-9.5 mg/L; Temp. = 4.6-26.4•C; Alkalinity = 160.0 mg/L	0.010	-	356-d chronic study, effect on reproduction and progeny showed that reduction in survival was seen in the last 98 days; adult growth was reduced during intermediate stage.	Hermanutz *et al.*, 1992
	adult	F, M,1	selenite	179.0	pH = 8.0; D.O. = 3.6-9.5 mg/L; Temp. = 4.6-26.4•C; Alkalinity = 160.0 mg/L	0.300	-	356-d chronic study, and effect on reproduction and progeny showed that complete mortalityresulted from this conc.; adult growth was reduced during intermediate stage.	
	adult	F, M,1	selenite	179.0	pH = 8.0; D.O. = 3.6-9.5 mg/L; Temp. = 4.6-26.4•C; Alkalinity = 160.0 mg/L	0.010	-	40 wks, exposure before spawning, resulted in reduced embryo and larval survival and produced larvae with a high incidence of edema, lordosis, and internal hemorhaging	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Lepomis macrochirus (bluegills)	adult	F, M,1	selenite	179.0	pH = 8.0; D.O. = 3.6-9.5 mg/L; Temp. = 4.6-26.4•C; Alkalinity = 160.0 mg/L	0.300	-	40 wks, exposure before spawning, resulted in reduced embryo and larval survival and produced larvae with a high incidence of edema, lordosis, and internal hemorhaging	Hermanutz *et al.*, 1992
	-	-	selenite	-	-	30.700	-	7-d LC50, mortality	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	27.700	-	8-d LC50, mortality	
	-	-	selenite	-	-	23.600	-	10-d LC50, mortality	
	-	-	selenite	-	-	20.500	-	12-d LC50, mortality	
	-	-	selenite	157.0	-	12.500	-	14-d LC50, mortality	
	-	-	-	-	-	17.600	-	14-d LC50, mortality	
Lepomis macrochirus (bluegills) (cont.)	adults exposed in the field and spawned in the laboratory	F,M,1	-	-	Alkalinity = 20.0 mg/L	0.009-0.012	-	2-yr study, mortality and deformity of larvae; total reproductive failure; in larvae 28.20 ug Se/g dry wt; carcass (minus gonad) = 5.9-7.8 ug Se/g wet wt; ovary = 6.9 wet wt (38.8-54.2 dry wt); testis = 4.37 wet wt	Gillespie and Baumann, 1986
	juveniles	F,M,1	-	-	Temp. = 21.0 •C	-	in diet 54.000 (satiation feeding-diet of mayfly nymph)	44-d, fish showed gross pathological and behavioral signs of selenosis; food avoidance was also seen; 75% mortality; skeletal muscle = 5 0-7.0 ug Se/g wet wt; liver = 8.0-86.0 wet wt	Finley, 1985; Adams, 1976
	juveniles	F,M,1	-	18.0	Temp. = 25.0 •C	-	in diet 45.000 (satiation feeding)	7-d, 100% mortality; whole body = 21-32 ug Se/g dry wt	Carolina Power and Light Company, 1985

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
...mis macrochirus ...gills) (cont.)	juveniles	F,M,1	-	19.0	Temp. = 25.0 •C	-	in diet 25.000-70.000 (satiation feeding)	61-d, 100% mortality; whole body conc. = 44.0-53.0 ug Se/g dry wt	Carolina Power and Light Company, 1985
	juveniles	F,M,1	-		Temp. = 26.0 •C; Alkalinity = 26.0 mg/L	0.009-0.012	in diet 21.000-73.000 (satiation feeding)	14-d, 100 % mortality; muscle = 13.1-17.5 ug Se/g dry wt; viscera = 27.5-37.5 dry wt	Duke Power Company, 1980
	larvae	F,M,1	selenite	318.0-330.0	-	0.400-2.000	-	48-d, LC50	Adams, 1976
	juvenile	F.M,1	selenite and selenate in water and seleno-L-methionine in diet	20.0-25.0	pH = 6.1-6.6; D.O. = 8.1-8.6 mg/L; Temp. = 20.0•C	0.005	in diet 5.100 as seleno-L-methionine	180-d study, hematological changes and gill damage that reduced respiratory capacity while increasing respiratory demand and oxygen consumption	Lemly, 1993
	juvenile	F.M,1	selenite and selenate in water and seleno-L-methionine in diet	20.0-25.0	pH = 6.1-6.6; D.O. = 8.1-8.6 mg/L; Temp. = 4.0•C	0.005	in diet 5.100 as seleno-L-methionine	180-d study, high Se in combination with low water temp. caused reduced activity and feeding, depletion of 50-80% of body lipid and significant mortality within 60 days.	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as $CaCO_3$)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Lepomis macrochirus (bluegills) (cont.)	juvenile	F,M,1	selenite and selenate (6:1 ratio)	134.0	pH = 8.1; Temp. = 17.0•C; Alkalinity = 60.0-65.0 mg/L	0.640	-	60-d LOAEC, increased mortality	Cleveland *et al* ., 1993
	-	-	selenite and selenate (6:1 ratio)	-	-	0.160-2.800	-	60-d, change in behaviour	
	-	-	selenite and selenate (6:1 ratio)	-	-	0.160-2.800	-	18-d LOC	
	juvenile	F,M,1	selenite and selenate (6:1 ratio)	134.0	pH = 8.1; Temp. = 17.0•C; Alkalinity = 60.0-65.0 mg/L	2.800	-	30-d, measurable changes in length and or weight of test organism; significant reduction in condition factor (K)	
	juvenile	F,M,1	seleno-L-methionine	134.0	pH = 8.1; Temp. = 17.0•C; Alkalinity = 60.0-65.0 mg/L	-	in diet 25.000 ug Se/g wet wt as seleno-L-methionine	30-d, significant reductions in condition factor (K)	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Lepomis macrochirus (bluegills) (cont.)	juvenile	F,M,1	seleno-L-methionine	134.0	pH = 8.1; Temp. = 17.0•C; Alkalinity = 60.0-65.0 mg/L	-	in diet 13.000 ug Se/g wet wt as seleno-L-methionine	90-d, significant reductions in condition factor (K)	Cleveland *et al*., 1993
	all life stages	F,M,1	-	-	Temp. = 20.0-38.0 •C	0.010	and 15.000-70.000 in diet	2 yr study, mortality and deformity of fry, juveniles and adults; significant decrease in standing crop; complete reproduction failure	Cumbie and Van Horn, 1978
Lepomis microlophus (redear sunfish)	-	-	-	-	-	0.005	-	contaminated lake resulted in substantial alterations in the liver including necrosis, cytoplasmic vacuolation, Kupffer cell proliferation and many abnormalities in ovaries; mean hepatic conc. of fish is 7.63 ug Se/g and 4.33 in ovaries	Sorensen, 1988
Micropterus salmoides (largemouth bass)	all life stages	F,M,1	-	-	Temp. = 20.0-38.0 •C	0.010	and 15.000-70.000 in diet	2 yr study, mortality and deformity of fry, juveniles and adults; significant decrease in standing crop; complete reproduction failure	Cumbie and Van Horn, 1978
Oncorhynchus kisutch (coho salmon)	larvae, fry	F,M,1	selenite	325.0-330.0	-	0.160	-	43-48-d LC50	Adams, 1976

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Oncorhynchus mykiss (rainbow trout)	-	-	-	-	-	-	in diet 10.000-13.000	results indicate reduced growth rates in rainbow trout	Hilton *et al.*, 1980; Hilton and Hodson, 1983; and Hicks *et al.*, 1984
	-	-	selenate	45.0	-	2.891	-	chronic effect, early life stage	Spehar, 1986
	egg	F,M,1	-	28.0	-	0.030-0.170	-	60-d, significant number of mortalities	Goettl and Davies, 1976a
	egg	F,M,1	-	28.0	-	0.030-0.170	-	12-mos, significant mortality	
	-	-	selenite	135.0	-	0.047	-	41-d (early life stage), reduced hatch of eyed embryos	Hodson *et al.*, 1980
	eyed eggs	F,M,1	-	135.0	Temp. = 0•C	0.028	-	post fertilization through hatching, significantly reduced hatching	
	-	-	selenite	135.0	-	0.053	-	50-wk, decreased iron in blood	
	-	-	-	-	-	-	in diet 5.410-6.920	9-d LC50	
	-	-	selenite	330.0	-	2.700-2.750	-	5-d LC50	Adams, 1976
	-	-	selenite	.334.0	-	0.250	-	21-d study, results showed reduced growth in trout fry	
	-	-	selenite	334.0	-	0.460	-	21-d LC50	
	-	-			-	0.290	-	96-d LC50	
	-	-	selenite	325.0	-	0.280	-	96-d LC50	
	larvae	F,M,1	selenite	325.0-330.0	-	0.500	-	48-d LC50, mortality	
	-	-	-	-	-	0.060-0.130	-	life cycle LC50	USEPA, 1980
	embryos	-	-	-	-	0.080	-	1 yr study, fish developed external deformities	Goettl and Davis, 1976a

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Oncorhynchus mykiss (rainbow trout)	sac fry (21.7 mm, 0.075 g)	F, M, 1	selenite	272.0	pH = 7.4; Temp. = 12.0•C; Alkalinity = 237.0 mg/L	0.047	-	90-d, significant mortality; whole body=1.07 ug Se/g wet wt in survivors; length was reduced at 30 and 60 days	Hunn *et al.*, 1987
	sac fry (21.7 mm, 0.075 g)	F, M, 1	selenite	272.0	pH = 7.4; Alkalinity = 237.0 mg/L	0.100	-	90-d study, showed survival significantly reduced; whole body=2.65 ug Se/g wet wt in survivors; length and wt. were significantly reduced after 90 days	
	sac fry (21.7 mm, 0.075 g)	F, M, 1	selenite	272.0	pH = 7.4; Alkalinity = 237.0 mg/L	0.012	-	30, 60 and 90-d studies, results of study indicate safe level of 0.010 mg/L for inorganic Se would not sig. affect growth but conc. near this level (0.012) reduce levels of calcium in backbone	
	-	-	selenite	272.0	-	0.055	-	90-d LC50	
Oncorhynchus mykiss (rainbow trout) (cont.)	juveniles	F,M,1	selenite	28.0	Temp. = 11.0•C	-	in diet 8.900	42-wk, significant mortality	Goettl and Davies, 1977b
	-	-	selenate	104.0	-	5.000	-	28-d EC50, death and deformity	Birge, 1978; Birge and Black, 1977; Birge *et al.*, 1980
	-	-	selenite	-	-	0.044	-	increased mortality	Davis *et a* l., 1988

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Onchorhynchus tshawytscha (chinook salmon)	egg to 90 day	F, M, 1	selenate : selenite (6: 1 ratio)	612.0	pH = 7.8; Temp. = 12.0•C; Alkalinity = 215.0 mg/L	0.035	-	well-water (30, 60 and 90-d) (0.250, 0.5, 1, 2 and 4 ratio,1= 1.4 B, 0.049 Mo, and 0.035 Se) conc. of Se in salmon were correlated with reduced survival and growth of fish in well water	Hamilton and Wiedmeyer, 1990
	0.3 g	F, M, 1	Se as (6: 1 of Na2Se04/ Na2Se03)	371.0	pH = 7.8; Temp. = 12.0•C; Alkalinity = 215.0 mg/L	0.035	-	freshwater (30, 60 and 90-d) (0.250, 0.5, 1, 2 and 4 ratio,1= 1.4 B, 0.049 Mo, and 0.035 Se) whole-body conc. of Se increased with increasing exposure conc.; reduced survival in a 15-d seawater challenge test	
	-	-	-	-	-	3.200-5.300	-	30-d, measurable changes in length and/or weight of test organism	Hamilton *et al.*, 1990
	swim-up larvae	F, M, 1	selenomethionine	210.0	pH = 7.7; Temp. = 13.7•C; Alkalinity = 109 mg/L	-	in diet 3.200-35.400 ug Se/g wet wt (mosquito-fish from San Luis Drain or fortified with selenomethionine)	90 d freshwater study, survival was reduced in fish fed • 9.6 of either diet; reduced growth in fish fed • 5.300 of SLD diet • 18.200 fortified diet; reducedgrowth, whole-body concs. and survival, strongly correlated to concs. of Se in both diets	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Onchorhynchus tshawytscha (chinook salmon)	fingerlings 70 mm	F, M, 1	selenomethionine	-	pH = 7.4 for first 30 days and 6.9 for rest; Temp. = 12.6 for first 30 days and 13.3•C for rest; Alkalinity = 109 mg/L	-	in diet 3.200-35.400 ug Se/g wet wt (mosquitofish from San Luis Drain or fortified with selenomethionine)	120-d brackish water study, survival was unaffected but growth was reduced infish fed • 9.600 and 18.200 of SLD diet or 35.400 of selenomethionine diet. Survival was reduced in a 10-day seawater challenge test in fish fed 35.400 of either diet	Hamilton *et al.*, 1990
	fry	F, M, 1	-	371.0	Temp. = 12.0•C	0.017	-	30-d, significant mortality	Hamilton *et al.*, 1986
Onchorhynchus tshawytscha (chinook salmon) (cont.)	-	-	-	-	-	-	in diet 26.000 ug Se/g (not stated whether wet or dry wt)	30-d, measurable changes in length and or weight of test organism	Hamilton *et al.*, 1986 (cont.)

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Onchorhynchus tshawytscha (chinook salmon) (cont.)	parr	F,M,1	-	74.0	Temp. = 10.0•C	-	in diet 13.000 (from Se contaminated organisms, 3% body weight per day feeding)	6-wk, reduced smolting success; in survivors, whole body = 2.9 ug Se/g wet wt, 13.4 dry wt	Hamilton *et al.*, 1986 (cont.)
Perca flavescens (yellow perch)	-	-	selenite	10.2	-	4.800	-	10-d LC50	Klaverkamp *et al.*, 1983
Perca fluviatilis (European perch)	adult	F,M,1	-	-	-	5.600	-	in fish tissue LOAEC	Crane *et a* l., 1992
Perca fluviatilis (European perch) (cont.)	-	-	-	300.0	pH = 7.9; Temp. = 15.0•C	0.025	-	10-12-d, change in % hatch or time to hatch	
	adult	F, M, 1	selenate / selenite (60:40 ratio)	-	pH = 7.5-11.0	0.025	-	513-d chronic study, mean wt 71.38 g, Se conc in muscle and gonad, 5.63 ug Se/g wet wt and 6.96. Almost a 50% mortality	
	-	-	-	-	-	0.025	-	529-543-d, change in male or female reprocuctive ability	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (ug/g) dry wt	Effect	Reference
Pimephales promelas (fathead minnows)	adult	F,M,1	25% seleno-L-methionine, 50%selenate and 25% selenite	139.4	pH = 8.19; D.O. = 8.48 mg/L; Temp. = 25.7 •C; Alkalinity = 247.4 mg/L	-	in diet 20.000 and 30.000 ug Se/g wet wt	105-d study, growth significantly inhibited; no effect on the reproductive parameters	Ogle and Knight, 1989
	adult	F,M,1	25% seleno-L-methionine 50% selenate and 25% selenite	-	Temp. = 25•C	-	in diet 40.000 ug Se/g wet wt	in a range finding experiment, feeding and growth were reduced but no mortality attributed to starvationwas observed; at this and higher treatments, no spawning occurred	
	adult	F,M,1	25% seleno-L-methionine 50% selenate and 25% selenite	-	Temp. = 25•C	-	in diet 80.000 and 160.000 ug Se/g wet wt	in range finding experiment fish developed severe edema within 24 hrs and were not observed feeding during remainder of experiment	
Pimephales promelas (fathead minnows) (cont.)	adult	F,M,1	25% seleno-L-methionine 50% selenate and 25% selenite	-	Temp. = 25•C	-	in diet 5.000-30.000 ug Se/g wet wt	14-98-d, measurable changes in length and or weight of test organism	Ogle and Knight, 1989 (cont.)

Species	Life Stage	Data type	Chemical	Hardness (mg/L as $CaCO_3$)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Pimephales promelas (fathead minnows) (cont.)	adult	F,M,1	25% seleno-L-methionine 50% selenate and 25% selenite	-	Temp. = 25•C	-	in diet 5.000-30.000 ug Se/g wet wt	98-d, change in male and/or female reproductive ability	Ogle and Knight, 1989 (cont.)
	adult	F,M,1	25% seleno-L-methionine 50% selenate and 25% selenite	-	Temp. = 25•C	-	in diet 20.000 ug Se/g wet wt	LOAEC, from day 56 on, observable differences in mean weight of fish was obvious	
	embryos	F, M,1	selenite	-	-	0.010	-	1-yr study, 24.6% edema compared to control of 0.9%; and 23.4% occurance of lordosis compared to 5.6% in control; larvae rather than egg development is affected by Se	Schultz and Hermanutz, 1990
	-	-	selenite	-	-	4.500	-	5-d LC50, mortality	Cardwell *et al.*, 1976a
	-	-	selenite	-	-	3.200	-	6-d LC50, mortality	
	-	-	selenite	-	-	2.900	-	7-d LC50, mortality	
	-	-	selenite	220.0	-	0.113	-	chronic effect-early life stage	Kimball Manuscript
	-	-	selenite	220.0	-	0.420	-	8-d LC50 (fed)	
	-	-	selenate	45.0-47.0	-	0.566	-	chronic effect-early life stage	Spehar, 1986

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Pimephales promelas (fathead minnows) (cont.)	0.03 g (25-35 days old)	-	selenite	329.0	pH = 7.3; D.O. = 5.3-6.2 mg/L; Temp. = 25•C; Alkalinity = 332.o mg/L	0.600	-	14-d LC50, mortality (fed)	Halter *et al.*, 1980
	2 days old	-	selenite	329.0	pH = 7.3; D.O. = 5.3-6.2 mg/L; Temp. = 25•C; Alkalinity = 332.o mg/L	10.000	-	17-d, change in ability to grow to a more mature life stage and in time between separate life stages	
	2 days old	-	selenite	329.0	pH = 7.3; D.O. = 5.3-6.2 mg/L; Temp. = 25•C; Alkalinity = 332.o mg/L	40.000	-	17-d, change in % hatch or time to hatch	
Pimephales promelas (fathead minnows) (cont.)	-	F,M,1	-	-	-	0.010	-	1 yr (approx), malformations (extended operculums, pointed snouts, exaggerated mandible angles, humped backs, and missing scales	Hermanutz, 1992
	-	F,M,1	-	-	-	0.030	-	1 yr (approx), high mortality; malformations: extended operculums, pointed snouts, exaggerated mandible angles, humped backs, and missing scales	
	adult	-	selenite	157.0	-	2.100	-	9-d LC50	Cardwell *et al.*, 1976a,b

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
(fathead minnows) (cont.	larvae, adult	-	selenate	330.0-338.0	-	1.100-2.000	-	48-d LC50	Adams, 1976
	-	-	-	-	-	0.083-0.153	-	life cycle LC50	USEPA, 1980
KEY									
LC = Lethal Concentration		M = Measured							
EC = Effective Concentration		N = Nominal							
S = Static Test Method		NA = Not Available							
F = Flowthrough Test Method		1 = Primary							
		2 = Secondary							

Table 9.03: Acute toxicity of selenium to freshwater invertebrates

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anadara granosa (ark shell)	-	-	selenite	-	-	1.000	-	96-h, change in enzyme activity	Patel and Chandy, 1987
	-	-	selenite	-	-	1.000	-	96-h, hematological changes	
	-	-	selenite	-	-	2.000	-	96-h LC50, mortality	Patel *et a* l., 1988
Aplexa hypnorum (snail)	adult	S,M,2	selenite	50.6	-	53.000	-	LC50 or EC50	Brooke *et al.*, 1985
	adult	S,M,2	selenite	49.8	-	23.000	-	LC50 or EC50	
Brachionus calyciflorus (rotifer)	-	-	-	-	-	16.000	-	24-h LC50, mortality	Snell *et a* l., 1991
Ceriodaphnia affinis (cladoceran)	-	S,U,2	selenite	100.8	pH = 7.9; D.O. = 8.4 mg/L; Temp. = 21.5 •C	0.600	-	48-h LC50, offspring from organisms not previously exposed to Se	Owsley, 1984; Owsley and McCauley, 1986
	-	S,U,2	selenite	100.8	pH = 7.9; D.O. = 8.4 mg/L; Temp. = 21.5 •C	0.350	-	48-h LC50, offspring from adults previously exposed (raised in conc. ranging from 0.018-0.36 mg Se/L for 18-19 days)	
	-	S,U,2	selenite	100.8	pH = 7.9; D.O. = 8.4 mg/L; Temp. = 21.5 •C	0.760	-	24-h LC50, offspring from organisms not previously exposed to Se	
	-	S,U,2	selenite	100.8	pH = 7.9; D.O. = 8.4 mg/L; Temp. = 21.5 •C	0.390	-	24-h LC50, offspring from adults previously exposed (raised in conc. ranging from 0.018-0.36 mg Se/L for 18-19 days)	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Chironomus decorus (midge)	12-13 day old-4th instar	SR,M,2	selenate	84.6	pH = 7.6-7.8; D.O. = 7.5 mg/L; Temp. = 21.5 •C; Alkalinity = 64.3	0.010	(•2.110 in diet of *Selenastrum capricornutum*)	96-h, significant reduction in larval growth at tissue concentrations • 2.55 ug Se/g dry wt; not detectable amounts in tissue at 24 and 48 h	Malchow *et al.*, 1995
	12-13 day old-4th instar	SR,M,2	selenite	84.6	pH = 7.6-7.8; D.O. = 7.5 mg/L; Temp. = 21.5 •C; Alkalinity = 64.3	0.010	(•2.840 in diet of *Selenastrum capricornutum*)	96-h, significant reduction in growth seen only at 96 h; tissue conc. were below detection at 24 h, 3.11 ug Se/g at 48 h and 4.05 at 96 h.	
	12-13 day old-4th instar	SR,M,2	selenate	84.6	pH = 7.6-7.8; D.O. = 7.5 mg/L; Temp. = 21.5 •C; Alkalinity = 64.3	0.040	(•7.170 in diet of *Selenastrum capricornutum*)	24-96-h, significant reduction in larval growth is seen at both 24 and 96 h; not detectable amounts in tissue at 24 h, 3.34 ug Se/g dry wt at 48 h and 6.62 at 96 h	
Chironomus decorus (midge) (cont.)	12-13 day old-4th instar	SR,M,2	selenite	84.6	pH = 7.6-7.8; D.O. = 7.5 mg/L; Temp. = 21.5 •C; Alkalinity = 64.3	0.040	(•9.470 in diet of *Selenastrum capricornutum*)	24-96-h, significant reduction in larval growth at 96 h; not detectable amounts in tissue at 24 h and 4.47 ug Se/g dry wt at 48 h and 8.60 at 96 h	Malchow *et al.*, 1995 (cont.)
	-	-	selenate	-	-	25.000	-	48-h LC50	Davis *et al.*, 1988
	-	-	selenite	-	-	50.000	-	48-h LC50	
	-	-	selenomethionine	-	-	< 200.000	-	48-h LC50	
Chironomus plumosus (midge)	-	S,U,2	selenite	39.0	-	24.150	-	LC50 or EC50	Mayer and Ellersieck, 1986
	-	S,U,2	selenite	280.0	-	27.850	-	LC50 or EC50	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Chironomus plumosus	-	-	selenate : selenite (6:1 ratio)	-	-	9.340-14.300	-	48-h LC50	Ingersoll *et al.*, 1990
	-	-	selenite	-	-	7.950-14.600	-	48-h LC50	
	-	-	selenate	-	-	10.500-16.200	-	48-h LC50	
	-	-	selenate : selenite (6:1 ratio)	-	-	1.790-2.620	-	48-h LC50	
Colisa fasciata (giant gourami)	-	-	selenite	-	-	9.990	-	24-h LC50, mortality	Srivastava and Tyagi, 1985
	-	-	selenite	-	-	5.770	-	48-h LC50, mortality	
	-	-	selenite	-	-	4.340	-	72-h LC50, mortality	
	-	-	selenite	-	-	2.650	-	96-h LC50, mortality	
Culex fatigans (mosquito larvae)	-	-	-	-	-	<3.100	-	48-h LC50	Nassos *et al.*, 1980
Daphnia magna (water flea)	-	-	-	-	-	0.220	-	48-h LC50, mortality	LeBlanc, 1980
	-	-	-	-	-	0.660	-	24-h LC50, mortality	
	-	S,U,2	selenite	72.0	-	0.430	-	48-h LC50, mortality	
	-	-	selenite	-	-	0.430	-	48-h LC50, mortality	
	-	-	-	-	-	2.620	-	48-h LC50, immobility	Ingersoll *et al.*, 1990
	-	-	-	-	-	9.340	-	48-h LC50, immobility	
	-	-	selenate : selenite (6:1 ratio)	-	-	1.790-2.620	-	48-h LC50	
	-	-	selenite	-	-	0.700-3.020	-	48-h LC50	
	-	-	selenate	-	-	2.560-4.070	-	48-h LC50	
	-	-	selenite	-	-	0.600	-	96-h LC50	Davis *et a*l., 1988
	-	-	selenate	-	-	2.400	-	96-h LC50	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as $CaCO_3$)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Daphnia magna (water flea) (cont.)	-	-	seleno-methionine	-	-	0.040	-	96-h LC50	Davis *et a* l., 1988 (cont.)
	-	-	selenite	-	-	1.100	-	48-h LC50	
	mid instar	-	selenite	329.0	pH = 7.3; S.O. = 5.3-6.2 mg/L; Temp. = 25.0•C; Alkalinity = 332.0 mg/L	0.710		48-h LC50, mortality (EC50 (fed))	Halter *et al.*, 1980
	mid instar	-	selenite	329.0	pH = 7.3; S.O. = 5.3-6.2 mg/L; Temp. = 25.0•C; Alkalinity = 332.0 mg/L	0.430		96-h LC50, mortality (EC50 (fed))	
	-	S,U,2	selenite	214.0	-	2.500	-	48-h EC50 (river water)	Bringmann and Kuhn, 1959a,b
	-	S,M,2	selenite	129.5	-	1.100	-	LC50 or EC50	Dunbar *et al.*, 1983
	-	S,M,2	selenate	129.5	-	5.300	-	LC50 or EC50	
	-	S,M,2	selenite	138.0	-	0.450	-	LC50 or EC50	Boyum, 1984
	-	S,M,2	selenate	138.0	-	1.010	-	LC50 or EC50	
	<24 hr	S,U,2	selenite	-	-	0.215	-	LC50 or EC50	Adams and Heidolph, 1985
	<24 hr	-	selenite	-	-	0.685	-	48-h EC50 (fed)	
	-	S,U,2	selenite	40.0	-	0.870	-	LC50 or EC50	Mayer and Ellersieck, 1986
	<24 hr	S,U,2	selenite	280.0	-	2.370	-	LC50 or EC50	
	-	-	selenite	-	-	1.000	-	48-h LC50	
	-	-	selenite	-	-	3.000	-	48-h LC50	
	-	S,M,2	selenate	48.1	-	0.570	-	LC50 or EC50	Brooke *et al.*, 1985

Species	Life Stage	Data type	Chemical	Hardness (mg/L as $CaCO_3$)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Daphnia magna (water flea) (cont.)	-	-	selenite	214.0	-	16.000	-	24-h LC50	Bringmann and Kuhn, 1977a
	-	-	selenite	214.0	-	0.010	-	24-h EC50 (swimming)	Bringmann and Kuhn, 1977b
	-	S,M,2	selenite	220.0	-	1.220	-	48-h LC50 (fed)	Kimball, Manuscript
	-	-	-	-	-	<0.250	-	48-h LC50	Nassos *et al.*, 1980
	neonate	SR,M,2	selenate	-	pH = 8.2; D.O. = 8.6 mg/L; Temp. = 20.0 •C	2.840	-	48-h LC50 (increasing sulfate conc. in later studies, was shown to decrease the toxicity)	Maier *et a*l., 1993
	neonate	SR,M,2	selenite	-	pH = 8.2; D.O. = 8.6 mg/L; Temp. = 20.0 •C	0.550	-	48-h LC50 (increasing sulfate conc. in later studies, was shown to vary the toxicity)	
	neonate	SR,M,2	seleno-DL-methionine	-	pH = 8.2; D.O. = 8.6 mg/L; Temp. = 20.0 •C	0.310	-	48-h LC50, immobilization was an acute sublethal response (increasing sulfate conc. in later studies, was shown not to effect the toxicity)	
Daphnia magna (water flea) (cont.)	neonate	SR,M,2	seleno-DL-cystine	-	pH = 8.2; D.O. = 8.6 mg/L; Temp. = 20.0 •C	2.010	-	48-h LC50, immobilization was an acute sublethal response	Maier *et a*l., 1993 (cont.)
	neonate	SR,M,2	seleno-DL-methionine	-	-	0.045	-	48-h IC50	
	neonate	SR,M,2	seleno-DL-cystine	-	-	0.520	-	48-h IC50	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as $CaCO_3$)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Daphnia magna (water flea) (cont.)	adults	-	selenite	-	pH = 8.4; Temp. = 22.0 °C	1.650	-	24-h LC50	Johnston, 1987
	adults	-	selenate	-	pH = 8.4; Temp. = 22.0 °C	1.510	-	24-h LC50	
	adults	-	selenite	-	pH = 8.4; Temp. = 22.0 °C	0.680	-	48-h LC50	
	adults	-	selenate	-	pH = 8.4; Temp. = 22.0 °C	0.750	-	48-h LC50	
	juveniles	-	selenate	-	pH = 8.4; Temp. = 22.0 °C	0.550	-	48-h LC50	
	eggs and embryos	-	selenate	-	pH = 8.4; Temp. = 22.0 °C	1.400	-	72-h LC50	
	adult	-	selenite	-	-	0.440	-	96-h LC50	
	adult	-	selenate	-	-	0.580	-	96-h LC50	
	-	-	selenate	-	-	5.300	-	48-h LC50	Dunbar *et al.*, 1983
Daphnia pulex (cladoceran)	-	S,M,2	selenite	46.4	-	3.870	-	96-h LC50	Reading, 1979; Reading and Buikema, 1983
	-	-	selenite	-	-	3.870	-	48-h LC50	Davis *et al.*, 1988
	-	-	selenite	-	-	0.130	-	96-h LC50, cellular damage	
Daphnia pulicaria (cladoceran)	-	S,M,2	selenate	138.0	-	0.246	-	LC50 or EC50	Boyum, 1984
	-	-	selenite	-	-	0.006	-	96-h LC50	Davis *et al.*, 1988

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Dugesia dorotocephala (turbellarian, flatworm)	-	-	-	-	-	1.000-10.000	-	1-h, behaviour	Kapu and Schaeffer, 1991
Gammarus pseudolimnaeus (amphipod)	adult	S,M,2	selenite	48.3	-	4.500	-	LC50 or EC50	Brooke *et al.*, 1985
	adult	S,M,2	selenate	46.1	-	0.075	-	LC50 or EC50	
	adult	S,M,2	selenite	53.6	-	1.700	-	LC50 or EC50	Brooke, 1987
	adult	S,M,2	selenate	51.0	-	0.057	-	LC50 or EC50	
Hyallela azteca (amphipod, scud)	2 mos	SR,M,2	selenite	132.7	pH = 8.6; D.O. = 7.67 mg/L; Temp. = 25.0 •C; Alkalinity = 301.85 mg/L	1.003	-	48-h LC50, effects were 4X more toxic than selenate at this time period	Brasher and Ogle, 1993
Hyallela azteca (amphipod, scud) (cont.)	2 mos	SR,M,2	selenate	132.7	pH = 8.6; D.O. = 7.67 mg/L; Temp. = 25.0 •C; Alkalinity = 301.85 mg/L	4.309	-	48-h LC50	Brasher and Ogle, 1993 (cont.)
	2 mos	SR M,2	selenite	132.7	pH = 8.6; D.O. = 7.67 mg/L; Temp. = 25.0 •C; Alkalinity = 301.85 mg/L	0.676	-	96-h LC50, effects were 3X more toxic than selenate at this time period	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Hyallela azteca (amphipod, scud) (cont.)	2 mos	SR,M,2	selenate	132.7	pH = 8.6; D.O. = 7.67 mg/L; Temp. = 25.0 •C; Alkalinity = 301.85 mg/L	1.868	-	96-h LC50	Brasher and Ogle, 1993 (cont.)
	adult	F,M,1	selenite	329.0	pH = 7.3; S.O. = 5.3-6.2 mg/L; Temp. = 25.0•C; Alkalinity = 332.0 mg/L	0.940	-	48-h LC50, mortality	Halter *et al.*, 1980
	adult	F,M,1	selenite	329.0	pH = 7.3; S.O. = 5.3-6.2 mg/L; Temp. = 25.0•C; Alkalinity = 332.0 mg/L	0.340	-	96-h LC50 mortality	Halter *et al.*, 1980; Murphy, 1981
	-	F,U	selenate	336.8	-	0.760	-	LC50 or EC50	Adams, 1976
	-	-	selenite	-	-	1.000	-	96-h LC50	Davis *et a* l., 1988
	-	-	selenate	-	-	1.000	-	96-h LC50	
Hydra sp. (hydra)	adult	S,M,2	selenite	-	-	1.700	-	LC50 or EC50	Brooke *et al.*, 1985
	adult	S,M,2	selenate	53.6	-	7.300	-	LC50 or EC50	
Meretrix casta (bivalve)	-	-	selenite	-	-	1.000	-	96-h, change in enzyme activity	Patel *et a* l., 1988
Paratanytarsus parthenogeneticus (midge)	3rd instar	S,M,2	selenate	49.4	-	20.000	-	LC50 or EC50	Brooke *et al.*, 1985
Physa sp. (snail)	-	S,U,2	selenite	45.7	-	24.100	-	96-h LC50	Reading, 1979
	-	-	-	-	-	>10.000	-	48-h LC50	Nassos *et al.*, 1980
Scylla serrata (crab)	-	-	selenite	-	-	68.000	-	24-h LC50	Krishnaja *et al.*, 1987

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
(crab)	-	-	selenite	-	-	46.000	-	48-h LC50	Krishnaja *et al.*, 1987
	-	-	selenite	-	-	33.000	-	72-h LC50	
	-	-	selenite	-	-	33.000	-	96-h LC50	
Tanytarsus dissimilis (midge)	-	-	-	-	-	56.700	-	24-h LC50, mortality	Call *et al.*, 1983
	-	F,M,1	selenite	48.0	-	42.500	-	48-h LC50	
	-	-	-	-	-	42.400	-	96-h LC50	USEPA, 1980
Xenopus laevis (frog)	embryo	-	-	-	-	20.000	-	27-h LC50	Browne and Dumont, 1979
	embryo	-	-	-	-	10.000	-	61-h LC50	
	embryo	-	-	-	-	4.000	-	96-h LC50	
KEY									
LC = Lethal Concentration	F = Flowthrough Test Method								
EC = Effective Concentration	R = Renewal		1 = Primary						
IC = Inhibition Concentration	M = Measured		2 = Secondary						
S = Static Test Method									

Table 9.04: Chronic toxicity of selenium to freshwater invertebrates

Species	Life Stage	Data type	Chemical	Hardness (mg/L as $CaCO_3$)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Acroperus harpae (water flea)	-	-	selenate : selenite (60:40 ratio)	-	-	0.025	-	514-d, decrease in abundance	Crane *et a*l., 1992
Anadara granosa (ark shell)	-	-	selenite	-	-	1.000	-	4-6-d, change in enzyme activity	Patel *et a*l., 1988
Ceriodaphnia affinis (cladoceran daphnid)	-	-	selenate : selenite (60:40 ratio)	-	-	0.050-0.080	-	8-d, P1, F1, F2 and F3 generation showed changes in abundance	Owsley and McCauley, 1986
Chironomid ae (midge family)	-	-	selenate : selenite (60:40 ratio)	-	-	0.002-0.025	-	513-d, decrease in abundance	Crane *et a*l., 1992
Chironomus decorus (midge)	larvae	SR,M,1	selenate	-	pH = 7.5; D.O. = 7.9 mg/L; Temp. = 20.0°C	>0.001	in diet of *Ruppia maritima* up to ~2.000	14-d study, decrease in weight from 0.22 mg of midges (dw) compared to 0.37 in control	Alaimo *et al.*, 1994
	larvae	SR,M,1	selenate-11%, selenite-11%, organic Se-78%	-	pH = 7.8; D.O. = 8.4 mg/L; Temp. = 20.0°C	0.004	in diet of *Ruppia maritima up* to ~16.000	14-d study, decrease in weight to 0.17 mg of midges (dw) compared to control of 0.37	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Chironomus decorus (midge) (cont.)	larvae	SR,M,1	selenate-28%,selenite-62%, organic Se (10%)	-	pH = 7.4; D.O. = 7.9 mg/L; Temp. = 20.0•C	0.017	in diet of *Ruppia maritima* up to ~80	14-d study, decrease in weight of 0.12 mg of midges (dw) compared to control of 0.37	
	larvae	SR,M,1	selenate-81%, organic Se 19%	-	pH = 7.7; D.O. = 8.2 mg/L; Temp. = 20.0•C	0.032	in diet of *Ruppia maritima* below detection to ~105	14-d study, decrease in weight of 0.12 mg of midges (dw) compared to control of 0.37	
Chironomus riparius	less than 24 hrs	F,M,1	selenate : selenite (6:1 ratio)	137.6	pH = 7.98; Alkalinity = 71.2 mg/L	0.504	-	30-d, maximum acceptable toxicant concentration; change in the emergence from larval stage into the adult stage	Ingersoll *et al.*, 1990
	less than 24 hrs	F,M,1	selenate : selenite (6:1 ratio)	137.6	pH = 7.98; Alkalinity = 71.2 mg/L	•0.837	-	30-d, emergence time of adult midges was delayed	
Chydorus ovalis (water flea)	-	-	selenate : selenite (60:40 ratio)	-	-	0.010-0.025	-	~500-d, decrease in abundance	Crane *et a*l., 1992
Colisa fasciata (giant gourami)	-	-	selenite	-	-	2.250	-	5-d LC50	Srivastava and Tyagi, 1985
Daphnia magna (water flea)	24 hr or less	S, M,1	selenate	-	Temp. = 23.0•C	0.050-1.000	-	28-d, decreased survival (50-70% after 28 days); reduced # of offspring and a lower intrinsic growth rate were seen	Boyum and Brooks, 1988

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Daphnia magna (water flea)	24 hr or less	S, M,1	selenate	-	Temp. = 23.0•C	0.050-1.000	in diet of *C. reinhardti i* (grown in 0.050-1.000 mg/L in water)	28-d, organically bound Se present appears to alter rate of incorporation of inorganic Se due to competition (supposedly), from less toxic form; much better success rate was seen in D. magna fed algae with Se; no offspring were produced at 1.0 mg Se/L	Boyum and Brooks, 1988
	-	-	selenite	-	-	1.000	-	decreased reproduction	Davis *et a* l., 1988
	-	-	selenite	329.0	pH = 7.3; D.O. = 5.3-6.2; Temp. = 25.0•C; Alkalinity = 332.0 mg CaCO3/L	0.430	-	14-d LC50, mortality (fed)	Halter *et al.*, 1980
	less than 24 hrs	F,M,1	selenate : selenite (ratio 6 : 1)	283.0	pH = 7.8; Alkalinity = 255.0 mg/L	0.115	-	21-d, maximum acceptable toxicant concentration affecting growth	Ingersoll *et al.*, 1990
	less than 24 hrs	F,M,1	selenate : selenite (ratio 6 : 1)	283.0	pH = 7.8; Alkalinity = 255.0 mg/L	0.085	-	21-d, reduction in adult dry wt	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Daphnia magna (water flea)	less than 24 hrs	F,M,1	selenate : selenite (ratio 6 : 1)	283.0	pH = 7.8; Alkalinity = 255.0 mg/L	0.156	-	21-d, slight reduction in available female reproductive days; reduction in intrinsic rate of natural growth increase; reduction in adult dry wt and body length of offspring; abundance changes	Ingersoll *et al.*, 1990
	less than 24 hrs	F,M,1	selenate : selenite (ratio 6 : 1)	283.0	pH = 7.8; Alkalinity = 255.0 mg/L	0.348	-	21-d, abundance changes; reduction in percent survival and total young per female reproduction days and total young	
	less than 24 hrs	F,M,1	selenate : selenite (ratio 6 : 1)	283.0	pH = 7.8; Alkalinity = 255.0 mg/L	0.711-1.410	-	21-d, mortality	
Daphnia ma gna (water flea) (cont.)	<24 hr	-	selenite	240.0-310.0	-	0.162	-	21-d life cycle EC50 (fed)	Adams and Heidolph, 1985
	-	-	selenite	220.0	-	0.092	-	chronic value, life cycle	Kimball, Manuscript
	-	-	selenate	129.5	-	1.870-2.000	-	7-d LC50 (fed)	Dunbar *et al.*, 1983
	-	-	-	-	-	0.240	-	28-d LC50	USEPA, 1980
	-	-	-	-	-	0.070-0.120	-	life cycle LC50	
	-	-	selenate	-	-	0.025-0.25	-	17-d-LC50, growth measured over instars 1-5 was shown to be supressed and reproduction over instars 6-9 was shown to have reduced egg production	Johnston, 1987

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g dry) wt.	Effect	Reference
***Daphnia pu*lex** (cladoceran)	-	-	selenite	46.4	-	0.693	-	chronic value, life cycle	Reading, 1979; Reading and Buikema, 1983
	-	-	-	-	-	0.600-0.800	-	life cycle LC50	USEPA, 1980
	-	-	selenite	-	-	0.200-0.800	-	decrease in filtration rate	Davis *et a*l., 1988
Entosiphion sulcatum (protozoan)	-	-	selenite	-	-	0.003	-	decreased reproduction	Davis *et a*l., 1988
Ergasilus sp. (parasitic copepod)	-	-	selenate : selenite (60:40 ratio)	-	-	0.025	-	514-d, decrease in abundance	Crane *et a*l., 1992
Eurycercus lamellatus (water flea)	-	-	selenate : selenite (60:40 ratio)	-	-	0.002-0.025	-	514-d, decrease in abundance	Crane *et a*l., 1992
Gastrophryna carolineasis (narrow-mouthed toad)	embryo, larva	-	selenate	195.0	-	0.090	-	7-d EC50, death and deformity	Birge, 1978; Birge and Black, 1977; Birge *et al.*, 1979
Graptoleberis testudinaria (water flea)	-	-	selenate : selenite (60:40 ratio)	-	-	0.002-0.025	-	514-d, decrease in abundance	Crane *et a*l., 1992
Hyalella azteca (scud)	-	-	selenite	329.0	pH = 7.3; D.O. = 5.3-6.2; Temp. = 25.0°C; Alkalinity = 332.0 mg CaCO3/L	0.070	in diet *Cladophora* which may have accumulated Se	14-d LC50, mortality (fed)	Halter *et al.*, 1980

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Hyalella azteca (scud)	2 mos	SR,M,2	selenite	132.7	pH = 8.6; D.O. = 7.7 mg/L; Temp. = 25.0°C; Alkalinity = 301.9 mg/L	0.502	-	10-d LC50	Brasher and Ogle, 1993
Hyalella azteca (scud)	2 mos	SR,M,2	selenate	132.7	pH = 8.6; D.O. = 7.7 mg/L; Temp. = 25.0°C; Alkalinity = 301.9 mg/L	1.135	-	10-d LC50	Brasher and Ogle, 1993 (cont.)
	-	-	selenite	-	-	0.200	-	reproduction effects-caused significant reduction in # of young per female (no effect seen in conc. as high as 0.700 of selenate	
Lymnaea stagnalis (snail)	-	-	selenite	-	-	3.000	-	7.5-d LC50	Van Puymbroeck *et al.*, 1982
	-	-	selenate	-	-	15.000	-	6-d LC50	
Moinodaphnia macleayi (water flea)	-	-	-	-	-	0.002	-	5-d, 100% mortality	Hyne *et al.*, 1993
Orconectes immunis (crayfish)	-	-	-	-	-	0.100-1.000	-	osmoregulatory changes	Davis *et a*l., 1988
Tubifex tubifex (tubificid worm)	-	-	selenate : selenite (60:40 ratio)	-	-	0.025	-	513-d, abundance decrease	Crane *et a*l., 1992

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Simocephalus espinosus	-	-	selenate : selenite (60:40 ratio)	-	-	0.002-0.025	-	513-d, abundance decrease	Crane *et a*l., 1992
Xenopus laevis (african clawed frog)	tadpole	-	selenite	-	-	1.520	-	7-d LC50	Browne and Dumont, 1979
	embryo	-	-	-	-	2.000	-	113-h LC50	
	tadpole	-	-	-	-	8.000	-	3-d LC50	
	tadpole	-	-	-	-	2.600	-	5-d LC50	
	-	-	selenite	-	-	2.000	-	1-7-d, cellular damage	Browne and Dumont, 1980
KEY									
LC = Lethal Concentration			M = Measured						
EC = Effective Concentration			1 = Primary						
S = Static Test Method			2 = Secondary						
F = Flowthrough Test Method									

Table 9.05: Toxicity of selenium to freshwater algae and macrophytes

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Effect	Reference
Anabaena cylindrica	-	-	selenite	-	-	24.000	14-d, reduced growth	Moede *et a*l., 1980
(blue green algae)	-	-	selenate	-	-	22.100	14-d, reduced growth	
Anabaena flos-aquae (blue-green algae	-	F,M,1	selenite	-	-	3.000	10-d study, significant effect on chlorophyll a formation algal tissue selenium levels =1071.0 ug Se/g	Kiffney and Knight, 1990
	-	F,M,1	selenate	-	-	3.000	10-d study, significant effect on chlorophyll a formation algal tissue selenium levels =743.50 ug Se/g	
	-	F,M,1	selenite	-	-	5.000	10-d study, significantly impairs chlorophyll a formation-results indicate complete inhibition; algal tissue selenium levels = 6072.0 ug Se/g	
	-	F,M,1	selenate	-	-	5.000	10-d study, significantly impairs chlorophyll a formation-results indicate complete inhibition; algal tissue selenium levels = 1217.7 ug Se/g	
	-	F,M,1	selenite	-	-	10.000	10-d study, significantly impairs chlorophyll a formation-results indicate complete inhibition; algal tissue selenium levels = 9365.2 ug Se/g	

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Effect	Reference
Anabaena flos-aquae (blue-green algae	-	F,M,1	selenate	-	-	10.000	10-d study, significantly impairs chlorophyll a formation-results indicate complete inhibition; algal tissue selenium levels = 1312.7 ug Se/g	
	-	F,M,1	seleno-L-methionine	-	-	0.100	10-d study, significant effect on chlorophyll a formation algal tissue selenium levels =1956.6 ug Se/g	
	-	F,M,1	seleno-L-methionine	-	-	0.300	10-d study, significantly impairs chlorophyll a formation; algal tissue selenium levels = 3658.8 ug Se/g	
	-	-	selenite	-	-	4.000	96-h EC50, decrease in cell division	Davis *et a*l., 1988
	-	-	selenate	-	-	5.000	96-h EC50, decrease in cell division	
	-	-	selenomethionine	-	-	0.300	96-h EC50, decrease in cell division	
Anabaena nidulans (blue-green algae)	-	-	selenite	-	-	50.000	21% decrease in cell divisions	Davis *et a*l., 1988
	-	-	selenate	-	-	50.000	24% decrease in cell divisions	
Anabaena variabilis (blue-green algae)	-	-	selenite	-	-	15.000	6-18-d LC50	Kumar and Prakash, 1971
	-	-	selenate	-	-	17.000	10-18-d EC50	
	-	-	-	-	-	15.000-17.000	96-h LC50	
Anacystis nidulans (blue-green algae)	-	-	selenite	-	-	30.000	10-18-d EC50	Kumar and Prakash, 1971
	-	-	selenate	-	-	39.000	6-18-d LC50	
	-	-	-	-	-	4.000-30.000	96-h LC50	
Ankistrodesmus falcatus	-	-	selenate	-	-	0.010	decrease in cell division	Davis *et a*l., 1988

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Effect	Reference
Chlorella vulgaris (green alga)	-	-	selenite	-	-	5.480	90-120-d, reduced growth	De Jong, 1965
Euglena gracilis (algae)	-	-	-	-	-	5.920	15-d, reduced growth	Bariaud and Mestre, 1984
Lemna minor (duckweed)	-	-	-	-	-	2.400	96-h EC50, measurable change in length and/or weight of test organism	Wang, 1986
Microcoleus vaginatus (blue-green algae)	-	-	selenate	-	-	10.000	14-d, reduced growth	Vocke *et a*l., 1980
Microcystis aeruginisa (blue-green algae)	-	-	selenite	-	-	9.400	8-d, incipient inhibition	Bringmann and Kuhn, 1976; 1978a,b
mixed population (diatoms)	-	-	selenite	-	-	11.000	18-d, inhibited growth	Patrick *et al.*, 1975
Oedogonium cardiacum (algae)	-	-	-	-	-	<0.100	48-h LC50	Nassos *et al.*, 1980
Scenedesmus dimorphus (green algae)	-	-	selenite	-	-	24.000	14-d, reduced growth	Moede *et a*l., 1980
	-	-	selenate	-	-	22.100	14-d, reduced growth	
	-	-	selenite	-	-	40.000	100% decrease in cell division	Davis *et a*l., 1988
	-	-	selenate	-	-	40.000	100% decrease in cell division	
Scenedesmus obliquus (green algae)	-	-	selenate	-	-	0.100	14-d, reduced growth	Vocke *et a*l., 1980
Scenedesmus ovadricavda (green alga)	-	-	selenite	-	-	2.500	96-h, incipient inhibition (river water)	Bringmann and Kuhn, 1959a,b
Selenastrum capricornutum (freshwater green alga)	-	-	-	-	-	99.000	72-h EC50, measurable change in length and/or weight of test organism	Ibrahim and Spacie, 1990

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Effect	Reference
Selenastrum capricornutum (freshwater green alga)	-	-	-	-	-	96.000	96-h EC50, measurable change in length and/or weight of test organism	Ibrahim and Spacie, 1990
	-	-	-	-	-	7.930	96-h EC50, change in plant productivity indicated by change in 14C or CO2 uptake or oxygen production	
	-	-	-	-	-	75.000	5-d EC50, measurable change in length and/or weight of test organism	
	-	-	-	-	-	65.000	6-d EC50, measurable change in length and/or weight of test organism	
Selenastrum capricornutum (freshwater green alga) (cont.)	-	-	selenite	-	-	0.075	72-h, decreased dry wt and chlorophyl a	Foe and Knight, Manuscript
	-	-	selenite	-	-	2.900	4-d EC50	Richter, 1982
	-	-	selenate	-	-	0.199	4-d EC50	
	-	-	selenate	-	-	0.300	14-d, reduced growth	Vocke *et a* l., 1980
	-	-	4% selenite and 96% selenate	-	-	0.100	96-h, varying conc. of S showed that at 3.3 mg S/L algal Se level was 156.0 ppm dry wt and algal biomass was decreased	Williams *et al.*, 1994
	-	-	4% selenite and 96% selenate	-	-	0.100	96-h, varying conc. of S showed that at 33.0 mg S/L algal Se level was 11.0 ppm dry wt and algal biomass was decreased	
	-	-	selenite	-	-	0.100	20% decrease in cell division	Davis *et a* l., 1988

Species	Life Stage	Data type	Chemical	Hardness (mg/L as CaCO3)	Other Measured Parameters	Conc. in water (mg/L)	Effect	Reference
KEY								
LC = Lethal Concentration		M = Measured						
EC- Effective Concentration		N = Nominal						
S = Static Test Method		1 = Primary						
F = Flowthrough Test Method		2 = Secondary						

Table 9.06: Acute toxicity of selenium to marine fish

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L) in water	Conc. in diet (µg/g) dry wt	Effect	Reference
Apeltes quadracus (fourspine stickleback)	adult	S,U,2	selenite	30.0	-	17.350	-	96-h LC50	USEPA, 1980; Cardin, 1986
Cyprinodon variegatus (sheepshead minnow)	adult	-	-	-	-	7.400-67.100	-	96-h LC50	USEPA, 1980
	juvenile	S,U,2	selenite		-	6.700	-	LC50 or EC50	Heitmuller *et al.*, 1981
	juvenile	F,M,1	selenite	30.0	-	7.400	-	LC50 or EC50	Ward *et al.*, 1981
	-	-	-	-	-	26.000	-	48-h LC50	Heitmuller *et al.*, 1981
	-	-	-	-	-	13.000	-	36-h LC50	
	-	-	-	-	-	6.700	-	96-h LC50	
	-	-	-	-	-	2.000	-	96-h NOEC, mortality	
	-	-	-	-	-	4.400	-	96-h LC50	Ward *et al.*, 1981
Lagodon rhomboides (pinfish)	juvenile	S,U,2	selenite	30.0	-	0.600	-	96-h LC50	USEPA, 1980
Melanogrammus aeglifinus (haddock)	larvae	-	-	-	-	0.599	-	LC50 or EC50	Cardin, 1986
	larva	S,U,2	selenite	30.0	-	9.725	-	96-h LC50	USEPA, 1980; Cardin, 1986
Menidia menidia (Atlantic silverside)	juvenile	S,U,2	selenite	30.0	-	1.550	-	LC50 or EC50	Palawski *et al.*, 1985
Morone saxatilis (striped bass)	-	S,U,2	selenite		-	6.790	-	LC50 or EC50	Klauda, 1985
	prolarvae	F,M,1	selenate	3.5-4.2	-				

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L) in water	Conc. in diet (µg/g) dry wt	Effect	Reference
(striped bass)	juvenile	F,M,1	selenate	6.0-6.5	-	85.840	-	LC50 or EC50	Klauda, 1985
	larvae	-	selenate	-	Hardness = 4.0 5.0 mg CaCO3/L	13.020	-	96-h LC50 (control survival=77%)	
	63 days	S,U,2	selenite	-	Hardness = 40.0 mg CaCO3/L	1.325	-	LC50 or EC50	Palawski *et al.*, 1985
	63 days	S,U,2	selenite	-	Hardness = 285.0 mg CaCO3/L	2.400	-	LC50 or EC50	
	24 days	-	selenite	38.5-40.5	Hardness = 750.0-800.0 mg CaCO3/L; D.O. = near sat.; and Temp. = 17.0 •C	26.300	-	96-h LC50 (inflated bladder)	Chapman, 1992
	24 days	-	selenate	38.5-40.5		3.400	-	96-h LC50 (inflated bladder)	
	24 days	-	selenite	38.5-40.5		36.700	-	96-h LC50 (uninflated bladder)	
	24 days	-	selenate	38.5-40.5		3.000	-	96-h LC50 (uninflated bladder)	
	25 days	-	selenite	38.5-40.5	Hardness = 750.0-800.0 mg CaCO3/L; D.O. =	23.700	-	96-h LC50 (inflated bladder)	
	25 days	-	selenate	38.5-40.5		3.300	-	96-h LC50 (inflated bladder)	
Morone saxatilis (striped bass) (cont.)	25 days	-	selenite	38.5-40.5	(cont.) near sat.; and Temp. = 17.0 •C	incalculable results	-	96-h LC50 (uninflated bladder)	Chapman, 1992 (cont.)
	25 days	-	selenate	38.5-40.5		incalculable results	-	96-h LC50 (uninflated bladder)	
	31 days	-	selenite	38.5-40.5	Hardness = 750.0-	26.300	-	96-h LC50 (inflated bladder)	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L) in water	Conc. in diet (µg/g) dry wt	Effect	Reference
Morone saxatilis (striped bass) (cont.)	31 days	-	selenate	38.5-40.5	800.0 mg CaCO3/L; D.O. = near sat.; and Temp. = 17.0 •C	3.800	-	96-h LC50 (inflated bladder)	
	31 days	-	selenite	38.5-40.5		incalculable results	-	96-h LC50 (uninflated bladder)	
	31 days	-	selenate	38.5-40.5		1.600	-	96-h LC50 (uninflated bladder)	
	32 days	-	selenite	38.5-40.5	Hardness = 750.0-800.0 mg CaCO3/L; D.O. = near sat.; and Temp. = 17.0 •C	29.000	-	96-h LC50 (inflated bladder)	
	32 days	-	selenate	38.5-40.5		3.900	-	96-h LC50 (inflated bladder)	
	32 days	-	selenite	38.5-40.5		34.800	-	96-h LC50 (uninflated bladder)	
	32 days	-	selenate	38.5-40.5		1.900	-	96-h LC50 (uninflated bladder)	
Paralichthys dentatus (summer flounder)	embryo	S,U,2	-	30.2	-	3.497	-	LC50 or EC50	Cardin, 1986
	larvae	-	-	-	-	3.500	-	96-h LC50	USEPA, 1980
Pseudopleuronectes americanus (winter flounder)	larva	S,U,2	selenite	30.0	-	14.240	-	LC50 or EC50	Cardin, 1986
	larva	S,U,2	selenite	28.0	-	15.070	-	LC50 or EC50	
	larvae	-	-	-	-	14.250-15.100	-	96-h LC50	USEPA, 1980
KEY									
LC = Lethal Concnetrat	S = Static Test Method		M = Measu	1 = Primary					
EC= Effective Concent	F = Flowthrough Test Method			2 = Secondary					

Table 9.07: Chronic toxicity of selenium to marine fish

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Cyrinodon variegatus (sheepshead minnow)	-		selenite	27.0	-	0.675	-	Chronic effect-early life stage	Ward *et al.*, 1981
Morone saxatilis (striped bass)	wt-250 grams	F,M,1	-	33.0	Hardness = 30.0 mg CaCO3/L; pH = 6.9; Temp. = 20.0 •C	-	(diet of red shiners) whole body Se conc. 9.600 ug Se/g wet wt	80-d study, mod. behav., little increase in weight, reduced condition factor ; elevated Se conc in muscle, histological damage to the liver and trunk kidney; and death of all fish within 78 days.	Coughlan and Velte, 1989
	eggs 24 hr postfertil.	F,M,1	-	-	Temp. = 20.0-26.0 •C	0.090	-	post fertilization through 60-d posthatch, significant number of deformities	Klauda, 1986
	-	-	selenate	-	Hardness = 3.5 5.5 mg CaCO3/L	0.039-1.360	-	9-65-d, significant incidence of development anomalies of lower jaw	Klauda, 1985
	-	-	selenate	-	Hardness = 3.5 5.5 mg CaCO3/L	1.290	-	45-d, significant incidence of severe blood cytopathology	
KEY									
LC = Lethal Concentrat	1 = Primary	M = Measured							
EC = Effective Concent	2 = Seconda	N = Nominal							
S = Static Test Method		NA = Not Available							
F = Flowthrough Test Method									

Table 9.08: Acute toxicity of selenium to marine invertebrates

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Acartia clausi (copepod)	adult	S,U,2	selenite	30.0	-	2.110	-	EC50 or LC50	Lussier, 1986
	-	-	-	-	-	1.740	-	96-h LC50	USEPA, 1980
Acartia to nso (copepod)	adult	S,U,2	selenite	30.0	-	0.839	-	EC50 or LC50	Lussier, 1986
	-	-	-	-	-	0.800	-	96-h LC50	USEPA, 1980
Allorchestes compressa (amphipod)	-	-	-	-	-	4.800-6.200	-	96-h LC50	Ahsanullah and Palmer, 1980
Argopecten irradians (bay scallop)	-	-	selenite	-	-	0.255	-	96-h LC50, mortality	Nelson *et al.*, 1988
Callinectes sapidus (blue crab)	juvenile	S,U,2	selenite	30.0	-	4.600	-	96-h LC50	Ward *et al.*, 1981
Cancer magister (dungeness or edible crab)	-	-	selenite	-	-	>10.000	-	24-h LC50, mortality	Martin *et al.*, 1981
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.500	-	24-h, 15% mortality compared to control with 10% mortality	Glickstein, 1978
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	1.000	-	24-h, 20% mortality compared to control with 10% mortality	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	5.000	-	24-h, 15% mortality compared to control with 10% mortality	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt.	Effect	Reference
Cancer magister (dungeness or edible crab)	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	10.000	-	24-h, 55% mortality compared to control with 10% mortality	Glickstein, 1978
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.100	-	48-h, 25% mortality compared to control with 20% mortality	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.500	-	48-h, 25% mortality compared to control with 20% mortality	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	5.000	-	48-h, 40% mortality compared to control with 20% mortality	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	10.000	-	48-h, 100% mortality compared to control with 20% mortality	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.100	-	96-h, 30% mortality compared to control with 20% mortality; with levels of Hg added between 3 and 30 µg Hg/L, mortality ranged from 25-40%	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.500	-	96-h, 35% mortality compared to control with 20% mortality; with levels of Hg added between 3 and 30 µg Hg/L, mortality ranged from 30-50%	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Cancer magister (dungeness or edible crab) (cont.)	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	1.000	-	96-h, 45% mortality compared to control with 20% mortality; with levels of Hg added between 3 and 30 µg Hg/L, mortality ranged from 35-70%	Glickstein, 1978 (cont.)
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	5.000-10.000	-	96-h, 100% mortality compared to control with 20% mortality; with levels of Hg added between 3 and 30 µg Hg/L, mortality was 100%	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	5.090	-	48-h LC50 or EC50	
	1st stage zoeae	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	1.040	-	96-h LC50	
Crassostrea gigas (Pacific oyster)	embryo	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.010	-	48-h, 12.9% abnormal development compared to 9.3 in control (range from 14.6 to 86.4% with 2 to 10 µg Hg/L)	Glickstein, 1978
	embryo	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	0.100	-	48-h, 14.0% abnormal development compared to 9.3 in control (range from 12.7 to 81.7% with 2 to 10 µg Hg/L)	
	embryo	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	1.000	-	48-h, 9.7% abnormal development compared to 9.3 in control (range from 8.7 to 87.7% with 2 to 10 µg Hg/L)	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Crassostrea gigas (Pacific oyster)	embryo	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	10.000	-	48-h, 10.7% abnormal development compared to 9.3 in control (range from 16.2 to 99.0% with 2 to 10 µg Hg/L)	Glickstein, 1978
	embryo	S,U,2	selenite	33.8	pH = 8.1; D.O = 6.58 mg/L	>10.000	-	48-h EC50 or LC50	
	-	-	selenite	-	-	>10.000	-	48-h EC50, change in the ability to grow to a more mature life stage and in time between seperate life stages	Martin *et al.*, 1981
Cylaspis usitata (cumacean)	-	-	selenite	-	-	6.100	-	96-h LC50	Ahsanullah and Palmer, 1980
Mysidopsis bahia (opossum shrimp)	juvenile	S,U,2	selenite	-	-	0.600	-	96-h LC50, mortality	USEPA, 1978; USEPA, 1980
	egg	S,U,2	selenite	-	-	0.127-0.143	-	life cycle LC50	USEPA, 1980
	juvenile	F,M,1	selenite	15.0-20.0	-	1.500	-	LC50 or EC50	Ward *et al.*, 1981
Mysidopsis bahia (opossum shrimp) (cont.)	adult	-	-	-	-	1.500	-	96-h LC50	Ward *et al.*, 1981 (cont.)
Mytilus edulis (common bay mussel, blue mussel)	-	-	selenite	-	-	>10.000	-	48-h EC50, change in ability to grow to a mature life stage and in time between separate life stages	Martin *et al.*, 1981
	embryo	S,U,2	selenium oxide	33.8	-	>10.000	-	LC50 or EC50	
Notocallista sp. (bivalve)	juvenile	-	-	-	-	2.900	-	96-h LC50	Ahsanullah and Palmer, 1980
Panaous aztecus (brown shrimp)	juvenile	S,U	selenite	30.0	-	1.200	-	96-h LC50	Ward *et al.*, 1981

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Perna viri dis (green mussel)	-	-	selenite	-	-	1.000	-	96-h, change in enzyme activity	Patel *et a* l., 1988
Spisula solidissima (surf crab)	-	-	selenite	-	-	1.900	-	96-h LC50, mortality	Nelson *et al.*, 1988
KEY									
LC = Lethal Concentration	M = Measured								
EC = Effective Concentration	1 = Primary								
S = Static Test Method	2 = Secondary								
F = Flowthrough Test Method									

Table 9.09: Chronic toxicity of selenium to marine invertebrates

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Clibanarius vittatus (hermit crab)	-	-	-	10.0/20.0 /30.0/40. 0 ppt	-	100.000	-	survival time increased from 10 to 20 ppt of salinity and then decreased for 30 and again for 40 ppt- for organisms originating from two different sites	Wolfenberger, 1986
	-	-	-	10.0/20.0 /30.0/40. 0 ppt	-	100.000	-	survival time decreased from 10 to 20 ppt of salinity and then increased for 30 and decreased for 40 ppt- for organisms originating from two different sites	
	-	-	-	10.0/20.0 /30.0/40. 0 ppt	-	100.000	-	survival time decreased from 10 to 20 ppt of salinity and then increased for 30 and decreased for 40 ppt- for organisms originating from two different sites	
Crassostrea virginica (Eastern oyster)	adult	-	selenate	34	-	0.400	-	14 days, no significant effect on respiration rate of gill tissue	Fowler *et al.*, 1981
Mysidopsis bahia (mysid)	-	-	selenite	26	-	0.212	-	chronic value life cycle	USEPA, 1978; Ward *et al.*, 1981
	-	-	-		-	0.135	-	life cycle no effect	USEPA, 1980
Mytilus edulis (blue crab)	-	F,M,1	selenite	28.0-31.0	-	0.050	-	120-h, reduction in filtration rates by 86-100% is seen in all cases; under	Micallef and Tyler, 1990

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Mytilus edulis (blue crab)	-	F,M,1	selenite	28.0-31.0	-	0.05 Se + 0.0197 Hg	-	these laboratory conditions the Se was not able to protect the mussels from	Micallef and Tyler, 1990
	-	F,M,1	selenite	28.0-31.0	-	0.05 Se + 0.05 Hg	-	effect of Hg.	
	3.6 cm	F	selenite	-	-	0.050	-	15-50 days, bioaccumulation rate of inorganic Se is doubled and tripled (respectively with the addition of inorganic Hg and methyl mercury	Pelletier, 1986
	3.6 cm	F	organic	-	-	0.050	-	Less dramatic changes seen with organic Se. Phenomenon is not reciprocal	
KEY									
F = Flowthrough Test M	1 = Primary		M = Measured						
	2 = Secondary		N = Nominal						

Table 9.10: Toxicity of selenium to marine algae and macrophytes

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
Chlorella pyrenoidosa (green algae)	-	-	selenate	-	-	0.003	3-d study, conc. in algae reached 2,600-3,100 ug Se/g dry mass algae	Bennett *et al.*, 1986
	-	S	selenate	-	-	0.530-1.370	a near linear decrease in steady-state is seen with increase in conc. and a um	Bennett, 1988
	-	S	selenate	-	-	0.800	um IC50 value at sulfur conc. of 2.70 mg/L	
Chlorella sp. (green algae)	-	-	selenite	32.0	Temp. = 20.0°C	0.010-10.000	14-d-5, 12% slight decrease in growth with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982
	-	-	selenate	32.0	Temp. = 20.0°C	0.010	14-d, no effect on rate of cell growth with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0°C	10.000	4-5-d, 100% mortaltiy with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0°C	0.100	reduced growth with sulfate conc. one tenth of normal seawater (85 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0°C	1.000-10.000	100% mortaltiy with sulfate conc. one tenth of normal seawater (85 mg/L)	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
Cricosphaera elongata (marine unicellular algae)	-	-	selenite	-	-	0.100-100.000	14-d study, log cell density as cells/ml show little diff. between control and 0.1; a low cell density was observed at 10.0 and a very significantly low cell density at 100.0; selenite was more toxic than selenate	Boisson *et al.*, 1995
	-	-	selenate	-	-	0.100-100.000	14-d study, (conc. of 0.01, 1.0, 10.0, and 100 mg Se/L) show little diff. at 0.1, 10.0 and control but low cell density was seen for 100.0; low toxicity compared with selenite	
	-	-	selenite	-	-	0.100-1.000	96-h study, accumulation is seen in exponentially growing cells (but decreased within first two hours) and cells in the stationary phase which continued accumulating Se until a plateau was reached	
	-	-	selenate	-	-	0.100-1.000		
cyanobacteria and mixed microbial ecosystem	-	F,M,1	-	-	pH = 3.0-9.0	5.000-150.000	stepwise increments of 5 mg Se/L are added; Tolerance of cyanobacteria was seen to be 70 mg Se/L; cyanobacteria used in bioremediation in conjunction with bacteria; removal of Se from the water column was rapid	Bender *et* al., 1991
Dunaliella minuta (algae)	-	-	selenite	-	-	10.000	growth was affected above this conc.	Gotsis, 1980

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
Dunaliella primolecta (green algae)	-		selenite	-	-	4.600	20-d, increased growth; induced glutathione peroxidase	Gennity *et al.*, 1985a,b
	-	-	selenate	32.0	Temp. = 20.0°C	0.010	14-d, no effect on rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982
	-	-	selenate	32.0	Temp. = 20.0°C	0.100-1.000	14-d, reduction in rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0°C	10.000	4-5-d, 100% mortaltiy with sulfate conc. comparable to seawater (850 mg/L); 100% mortaltiy with sulfate conc. one tenth of normal seawater (85 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0°C	0.100	reduced growth with sulfate conc. one tenth of normal seawater (85 mg/L)	
	-	-	selenite	32.0	Temp. = [illegible]	0.100-10.000	intermediate results with sulfate conc. comparable to normal seawater (850 mg/L)	
	-	-	selenite	32.0	Temp. = 20.0°C	100.000	reduced growth with sulfate conc. one tenth of normal seawater (85 mg/L)	
Fucus spiralis L. (brown algae)	-	-	selenite	-	-	2.605	60-d, 1355% increase in growth of thalli	Fries, 1982
	-	-	selenate	-	-	2.605	60-d, 160% increase in growth of thalli	
Goniotrichum alsidii (macro-algae)	-	-	selenite	-	-	2.600	increased growth	Fries, 1982

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
(macro-algae)	-	-	selenate	-	-	2.600	increased growth	Fries, 1982
Pavlova lutheri (algae)	-	-	selenite	-	-	2.000	growth was affected above this conc.	Gotsis, 1980
Peridinopsis borgei (dinoflagellate)	-	-	selenite	-	-	0.00001-0.00005	70-75-d, maximum growth	Lindstrom, 1985
Platymonas sp. (green algae)	-	-	selenate	32.0	Temp. = 20.0•C	0.010	14-d, no effect on rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982
	-	-	selenate	32.0	Temp. = 20.0•C	0.100-1.000	14-d, reduction in rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	
Platymonas sp. (green algae) (cont.)	-	-	selenate	32.0	Temp. = 20.0•C	10.000	4-5-d, 100% mortaltiy with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982 (cont.)
	-	-	selenate	32.0	Temp. = 20.0•C	0.100-10.000	100% mortaltiy with sulfate conc. one tenth of normal seawater (85 mg/L)	
	-	-	selenite	32.0	Temp. = 20.0•C	0.100-10.000	increased growth with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenite	32.0	Temp. = 20.0•C	0.100-100.000	intermediate results with sulfate conc. one tenth of normal seawater (85 mg/L); no mortality even at 100	
Platymonas subcordiformis (green algae)	-	-	selenate	32.0	Temp. = 20.0•C	0.010	14-d, no effect on rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
Platymonas subcordiformis (green algae)	-	-	selenate	32.0	Temp. = 20.0•C	0.100-1.000	14-d, reduction in rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982
	-	-	selenate	32.0	Temp. = 20.0•C	10.000	4-5-d, 100% mortaltiy with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0•C	1.000-10.000	100% mortaltiy with sulfate conc. one tenth of normal seawater (85 mg/L)	
	-	-	selenite	32.0	Temp. = 20.0•C	0.100-10.000	increased growth with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenite	32.0	Temp. = 20.0•C	0.100-100.000	intermediate results with sulfate conc. one tenth of normal seawater (85 mg/L); no mortality even at 100	
Porphyridium cruentum (red algae)	-	-	selenite	-	-	4.600	27-d, increase growth; induced glutathione peroxidase	Gennity *et al.*, 1985a,b
	-	-	selenate	32.0	Temp. = 20.0•C	0.010-1.000	14-d study, 23-35% reduction in rate of cell population growth at sulfate concentration (850 mg/L) normally found in seawater;	Wheeler *et al.*, 1982
	-	-	selenate	32.0	Temp. = 20.0•C	10.000	4-5-d, 100% mortality at sulfate concentration (850 mg/L) normally found in seawater	
	-	-	selenate	32.0	Temp. = 20.0•C	1.000-10.000	100% mortality with sulfate concentrations one tenth of what is normally found in seawater (ex. 85 mg/L)	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
Porphyridium cruentum (red algae) (cont.)	-	-	selenite	32.0	Temp. = 20.0•C	0.010-100.000	no inhibitory effects were seen with full sulfate (850 mg/L) equivalent to level found in seawater;	Wheeler *et al.*, 1982
Porphyridium cruentum (red algae) (cont.)	-	-	selenite	32.0	Temp. = 20.0•C	100.000	some intermediate decrease in growth at 100 mg Se/L and one tenth the conc. of sulfate normally found in seawater (ex. 85 mg/L)	Wheeler *et al.*, 1982
Skeletonema costatum (diatom)	-	-	selenite	-	-	7.930	96-h, EC50 change in plant production (reduction in chlorophyll a)	USEPA, 1978
Thalassiosira aestivalis (diatom)	-	-	selenite	2.0-30.0	-	0.079	72-h, no effect on cell morphology	Thomas *et al.*, 1980
Tetraselmis chui (diatom)	-	-	selenate	32.0	Temp. = 20.0•C	0.010	14-d, no effect on rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	Wheeler *et al.*, 1982
	-	-	selenate	32.0	Temp. = 20.0•C	0.100-1.000	14-d, reduction in rate of cell population growth with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0•C	10.000	4-5-d, 100% mortaltiy with sulfate conc. comparable to seawater (850 mg/L)	
	-	-	selenate	32.0	Temp. = 20.0•C	1.000-10.000	100% mortaltiy with sulfate conc. one tenth of normal seawater (85 mg/L)	
	-	-	selenite	32.0	Temp. = 20.0•C	0.100-10.000	intermediate results with sulfate conc. comparable to seawater (850 mg/L)	

Species	Life Stage	Data type	Chemical	Salinity (g/kg)	Other Measured Parameters	Conc. (mg/L)	Effect	Reference
Tetraselmis chui (diatom)	-	-	selenite	32.0	Temp. = 20.0°C	0.100-100.000	intermediate results with sulfate conc. one tenth of normal seawater (85 mg/L); no mortality even at 100	Wheeler *et al.*, 1982
KEY								
LC = Lethal Concentration	1 = Primary		M = Measured					
S = Static Test Method	2 = Secondary							
F = Flowthrough Test Method								

Table 10.01: Toxicity of selenium to wildlife

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards)	adult	F,M,1	selenite	-	3.500 (reduced from 5.000)	-	12-wk study, increased serum alanine amino-transferase (ALT) activity indicative of renal or hepatic dysfunction;	Fairbrother and Fowles, 1990
	adult male	-	selenite	-	3.500	-	80-d study, significant reduction of body weight compared to control	
	adult	F,M,1	selenomethionine	-	2.200	-	12-wk study, signif. impaired delayed-type hypersensitive (DTH) response to tuberculin; signif. increased ALT ; increased plasma glutathione peroxidase (GPX)	
	hatch to six weeks	F,M,1	selenite	-	-	10.000	6-wk study, larger livers than controls	Heinz *et a*l., 1988; Hoffman *et al.*, 1989
	hatch to six weeks	F,M,1	selenite	-	-	20.000	6-wk study, a decrease in food consumption and growth was seen	
	hatch to six weeks	F,M,1	selenite	-	-	40.000	6-wk study, resulted in 25% mortality; decrease in food consumption and growth; mortality may have been Se induced starvation	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards)	hatch to six weeks	F,M,1	selenite	-	-	80.000	6-wk study, resulted in 97.5% mortality; a decrease in food consumption and growth; mortality may have been Se induced starvation	Heinz *et a* l., 1988; Hoffman *et al.*, 1989
	hatch to six weeks	F,M,1	selenomethionine	-	-	20.000	6-wk study, a decrease in food consumption and growth was seen	
	hatch to six weeks	F,M,1	selenomethionine	-	-	40.000	6-wk study, resulted in 12.5% mortality; decrease in food consumption and growth; mortality may have been Se induced starvation	
	hatch to six weeks	F,M,1	selenomethionine	-	-	80.000	6-wk study, resulted in 100% mortality; a decrease in food consumption and growth; mortality may have been Se induced starvation	
	hatch to six weeks	F,M,1	selenomethionine	-	-	10.000	6-wk study, elavated plasma and hepatic, reduced glutathione (GSH) peroxidase activity compared to control	Hoffman *et al.*, 1989
	hatch to six weeks	F,M,1	selenomethionine	-	-	20.000	6 wk study, elevated: plasma GSH peroxidase activity, hepatic protein; decreased, malondialdehyde: hepatic GSH peroxidase activity, GSH (49%) and hepatic thiol (SH) (23%)	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt.	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	hatch to six weeks	F,M,1	selenomethionine	-	-	40.000	6-wk study, decrease in plasma and hepatic GSH peroxidase activity, SH (45%), glutathione (78%); elevated plasma GSSG reductase, oxidised glutathione (93%), hepatic protein and malondialdehyde	Hoffman *et al.*, 1989
	hatch to six weeks	F,M,1	selenite	-	-	10.000	6-wk study, elevated plasma GSSG reductase, (GSH) (28%)	
	hatch to six weeks	F,M,1	selenite	-	-	20.000	6-wk study, oxidised glutathione (73%) decreased hepatic protein	
	hatch to six weeks	F,M,1	selenite	-	-	40.000	6-wk study, decrease in hepatic protein, SH ; elevated plasma GSSG reductase, GSH (39%), oxidised glutathione (93%), and malondialdehyde (32%)	
	adult-males	F,M,1	selenomethionine	-	-	10.000	8-d study, showed that Se could be detected in the food and will be avoided by the mallards during feeding; avoidance appeared to be caused by a conditioned response due to illness and not aversion to taste.	Heinz and Sanderson, 1990

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (ug/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards)	adult-males	F,M,1	selenomethionine	-	-	20.000	8-d study, showed that Se could be detected in the food and will be avoided by the mallards during feeding; avoidance appeared to be caused by a conditioned response due to illness and not aversion to taste.	Heinz and Sanderson, 1990
Anas platyrhynchos (mallards) (cont.)	adult-males	F,M,1	selenomethionine	-	-	15.000-100.000	17 wk study, (initial exposure of 15.000 ug/g for 21 wk pre-study period)12 weeks of control diet and then 5 weeks of 100.000; 14.7% mortality; 39.3% weight loss; Se in liver = 35 ug/g wet wt	Heinz, 1993
	adult-males	F,M,1	selenomethionine	-	-	15.000-100.000	17 wk study, (no initial exposure)12 weeks of control diet and then 5 weeks of 100.000; 14.3% mortality; 41.2% weight loss; Se in liver = 40-53 ug/g wet wt; none of these were considered significant differences	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (ug/L)	Conc. in diet (ug/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	female-adults and offspring	F,M,1	selenomethionine	-	-	8.000	long term study, females had 4.6 young that survived to six days compared to 8.1 in control; 6.8% malformations in young compared to 0.6 in control; reduced survival in ducklings whose parents were fed Se even though ducklings were fed control diet.	Heinz *et al* ., 1989
	female-adults and offspring	F,M,1	selenomethionine	-	-	16.000	long term study, females had no young that survived to six days compared to 8.1 in control; 67.9% malformations in young compared to 0.6 in control; reduced survival in ducklings whose parents were fed Se even though ducklings were fed control diet.	
	female-adults and offspring	F,M,1	selenocystine	-	-	16.000	No impairment to reproduction was seen.	
	adult-male	F,M,1	selenomethionine	-	-	20.000	16-wk study, mortality was 25%; body weights sinificantly decreased after 1 wk; 4 wks after being returned to untreated diet, weight of birds was close to control birds; mortality may have been enhanced by cold weather	Heinz and Fitzgerald, 1993 (a)

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	adult-male	F,M,1	selenomethionine	-	-	40.000	16-wk study, mortality was 95% by 11 wks; body weights sinificantly decreased after 1 wk; 1 bird left at end of study died within 5 days after being returned to untreated diet; mortality may have been enhanced by cold weather	Heinz and Fitzgerald, 1993 (a) (cont.)
	adult-male	F,M,1	selenomethionine	-	-	80.000	16-wk study, mortality was 100% by wk 8; body weights sinificantly decreased after 1 wk; mortality may have been enhanced by cold weather	
	adult-male	F,M,1	selenomethionine	-	-	15.000	5-mos. study, (Nov to April), 1 of 46 died	Heinz and Fitzgerald, 1993 (b)
	adult-female	F,M,1	selenomethionine	-	-	15.000	5-mos. study, (Nov to April), 3 of 45 died	
	1 day old ducklings	F,M,1	selenomethionine	-	-	60.000	4-wk study, 22% protein in diets; duckling survival and growth was reduced (40% mortality) and livers had histopathological lesions.	Hoffman *et al.*, 1992
	1 day old ducklings	F,M,1	selenomethionine	-	-	60.000	4-wk study, 7% protein (isocaloric) in diets; 100% mortality	

Species	Life Stage	Data type	Chemical	Measured Parameter	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	1 day old ducklings	F,M,1	selenomethionine + sodium arsenate	-	-	15.000 to 60.000 Se + 200.000 As	4-wk study, 22% protein in diets; complete or partial alleviation of following Se toxic effects: mortality, impaired growth, hepatic lesions, lipid peroxidation, altered glutathione and thiol status	
	1 day old ducklings	F,M,1	selenomethionine + sodium arsenate	-	-	15.000 to 60.000 Se + 200.000 As	4-wk study, 7% protein (isocaloric) in diets; 53-73% mortality; much less alleviation of Se toxic effects	
	2 yr old male	F,M,1	selenomethionine	-	-	16.000	14 wk study (in spring), lower hemoglobin; linear dose response to GSSG and ratio to GSH; mean hepatic GSH and malondialdehyde	Hoffman *et al.*, 1991(b)
	2 yr old male	F,M,1	selenomethionine	-	-	32.000	14-wk study (in spring), same as 16 plus-10% mortality; histopathological effects including bile duct hyperplasia and hemosiderin pigmentation of the liver and spleen; lower hematocrit; elevated plasma alkaline phosphatase activity	
Anas platyrhynchos (mallards)	1 day old ducklings	F,M,1	selenomethionine	-	-	60.000	4-wk study, 22% protein in diets; duckling survival and growth was reduced (53% mortality) and livers had histopathological lesions on 25% of ducklings.	Hoffman *et al.*, 1991(a)

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	1 day old ducklings	F,M,1	selenomethionine	-	-	60.000	4-wk study, 7% protein (isocaloric) in diets; 100% mortality	Hoffman *et al.*, 1991(a)
	1 day old ducklings	F,M,1	selenomethionine + boric acid	-	-	15.000 to 60.000 Se + 200.000 B	4-wk study, 22% protein in diets; (up to 60% mortality); interactive effects resulted in further reduction in growth, and increases in plasma glutathione reductase activity, hematocrit hemoglobin and plasma protein conc.	
	1 day old ducklings	F,M,1	selenomethionine + boric acid	-	-	15.000 Se + 200.000 B	4-wk study, 7% protein (isocaloric) in diets; 27% mortality; enhanced accumulation of Se in liver; more enhanced syptoms seen due to interactive effects	
	1 day old ducklings	F,M,1	selenomethionine + boric acid	-	-	60.000 Se + 200.000 B	4-wk study, 7% protein (isocaloric) in diets; 100% mortality	
	adults and offspring	F,M,1	selenomethionine	-	-	10.000 fresh wt (diet contained about 10% moisture)	reproductive study, mainly teratogenic effects, reduced productivity and duckling survival; conc in eggs ranged from 2.9 to 5.6 ug/g wet wt and conc ranges in adult male and female livers were 6.1 to 12.0 and 2.6 to 6.2 respectively	Heinz *et a*l., 1987
	adults and offspring	F,M,1	selenite	-	-	10.000	mainly embryotoxic effects	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	adults and offspring	F,M,1	selenite	-	-	25.000	mainly embryotoxic effects, 1 male died after 57 days, significant reduction in weight of adults, females took longer to begin laying eggs and between laying intervals, reduced mean number of 21 day ducklings produced per female	Heinz *et a*l., 1987
	adults	F,M,1	selenite	-	-	100.000	11 of 12 died; none laid eggs before they died	
	adults and offspring	F,M,1	selenite	-	-	10.000	6-wk prior to reproduction, 3.6 % malformations	Hoffman and Heinz, 1988
Anas platyrhynchos (mallards) (cont.)	adults and offspring	F,M,1	selenite	-	-	25.000	6-wk prior to reproduction, 4.2% malformations; decrease: by 40-44% in total number eggs hatched, by 19% in embryonic wt at 18 d of incubation, by 6% in crown length; fourfold elevation in plasma uric acid conc. indicative of renal alteration	Hoffman and Heinz, 1988 (cont.)
	adults and offspring	F,M,1	selenomethionine	-	-	10.000	6-wk prior to reproduction, 13.1% malformations (often multiple); decrease: by 40-44% in total number eggs hatched; by 40% in plasma glutathione peroxidase activity, by 70% in sorbitol dehydrogenase activity	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	adults and offspring	F,M,1	selenomethionine	-	-	4.000	6 wk prior to reproduction, 1.4% malformation (compared to 0.5% at half this conc.) (including hydrocephaly, micropthalmia, lower bill defects and foot defects with ectrodactyly	Hoffman and Heinz, 1988 (cont.)
	adults and offspring	F,M,1	selenomethionine	-	-	8.000	6 wk prior to reproduction,6.8% malformation (compared to 0.5% at half this conc.) (including hydrocephaly, micropthalmia, lower bill defects and foot defects with ectrodactyly); decreased hatching by 36%	
	adults and offspring	F,M,1	selenomethionine	-	-	16.000	6 wk prior to reproduction, 67.9% malformation (compared to 0.5% at half this conc.) (including hydrocephaly, micropthalmia, lower bill defects and foot defects with ectrodactyly); decreased hatching by 91%	
	-	-	originates mostly form selenate in water and converts to organic form	-	0.300 in water entering Kesterson ponds	22.000-175.000 in plants, inverts., and fish from ponds	16.7% dead embryos in nest, 2.5% in eggs, 10.0% abnormal embryos or chicks in nest and 4.0 in eggs (eyes, legs/feet, beak and hydrocephaly)	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Anas platyrhynchos (mallards) (cont.)	-	-	-	-	* 0.0021	-	toxicity thresholds were devised for individual wildlife	Peterson and Nebeker, 1992
Ceryle alc yon (belted kingfisher)	-	-	-	-	* 0.0009	-	toxicity thresholds were devised for individual wildlife	Peterson and Nebeker, 1992
Cistothorus palustris (marsh wren)	-	-	-	-	* 0.0008	-	toxicity thresholds were devised for individual wildlife	Peterson and Nebeker, 1992
Fulica americana (American coot)	-	-	originates mostly form selenate in water and converts to organic form	-	0.300 in water entering Kesterson ponds	22.000-175.000 in plants, inverts., and fish from ponds	59.3% dead embryos in nest, 14.6% in eggs, 42.4% abnormal embryos or chicks in nest and 8.8 in eggs high mortality of hatchlings; no nests found in area in 1984-85 where 92 had been found in 1983; 94.4 and 96.6 µg Se/g in liver and kidney, respectively	Ohlendorf *et al.*, 1986; Ohlendorf *et al.*, 1988
Haliaeetus leucocephalus (bald eagle)	-	-	-	-	* 0.0019	-	toxicity thresholds were devised for individual wildlife	Peterson and Nebeker, 1992
Himantopus mexicanus (black-necked stilt)	-	-	originates mostly form selenate in water and converts to organic form	-	0.300 in water entering Kesterson ponds	22.000-175.000 in plants, inverts., and fish from ponds	16.7% dead embryos in nest, 5.8% in eggs, 17.6% abnormal embryos or chicks in nest and 6.8 in eggs (eyes, legs/feet, beak, hydrocephaly, exencephaly and wings)	Ohlendorf *et al.*, 1986; Ohlendorf *et al.*, 1988
Pandion haliaetus (osprey)		-	-	-	* 0.0013	-	toxicity thresholds were devised for individual wildlife	Peterson and Nebeker, 1992

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Podilymbus podiceps (eared grebe)	-	-	originates mostly form scienate in water and converts to organic form	-	0.300 in water entering Kesterson ponds	22.000-175.000 in plants, inverts., and fish from ponds	60.0% dead embryos in nest, 31.7% in eggs, 15.7% abnormal embryos or chicks in nest and 5.5 in eggs (eyes, legs/feet, beak, hydrocephaly, exencephaly and wings); high mortality of hatchlings	Ohlendorf *et al.*, 1986; Ohlendorf *et al.*, 1988
Zalophus californianus (California sea lion)	adult	-	-	-	-	fish diet: 1.010 ¨g Se/g wet wt in minnows and mackerel,	100% mortality; gross lesions of stomach interpreted as necrosis; ulcers in stomach were chronic and consisted of mucosal necrosis and fibroplasia; small lesions in brain; nonsupperative encephalitus; lungs hyperemic	Edwards *et al.*, 1989
	adult	-	-	-	-	1.060 in sardines and 0.700 in smelts	100% mortality; gross lesions of stomach interpreted as necrosis; large lesions in brain; nonsupperative encephalitus; lungs hyperemic	

Species	Life Stage	Data type	Chemical	Measured Parameters	Conc. in water (mg/L)	Conc. in diet (µg/g) dry wt	Effect	Reference
Zalophus californianus (California sea lion) (cont.)	adult	-	-	-	-	-	100% mortality; moderate multifocal pulmonary emphysema and atelectasis, moderated adrenal exhaustion and mild focal myopathy; skeletal muscle had occasional degenerate myofibers with nuclear proliferation and regeneration; no significant lesions	Edwards *et al.*, 1989 (cont.)
KEY								
LC = Lethal Concentrat	1 = Primary	= Measured						
S = Static Test Method	2 = Secondary	= Nominal						
F = Flowthrough Test Method								

Table 11.01: Effect of Selenium on agricultural crops

Organism/species	Effect concentration for Se (dry wt basis) and Se species	Effect/ comments	Test conditions	Reference
Alfalfa (***Medicago sativa***)	0.70 mg/kg in soil	60-d-Se conc. for whole plant was 4.7 mg/kg	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992
Alfalfa (***Medicago sativa***)	0.70 mg/kg in soil	145-d-Se conc. for whole plant was 10.6 mg/kg	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992
Alfalfa (***Medicago sativa***) L., Germain WL 512	0.25 mg/L as Na2SeO4	increase of B conc. from 0.5 to 3.0 mg/L resulted in an increase in yield by 17% and a slight decrease in levels of Se as ug Se/g dry wt; an increase in salinity from 0.5 to 3.0 dS/m resulted in a 22% decrease in yield and a 95% decrease in Se in plant	Greenhouse study; course grained silica sand; pH 6.5-7.0	Mikkelsen *et al.*, 1988
Alfalfa (***Medicago sativa***) L., Germain WL 512	0.50 mg/L as Na2SeO4	increase of B conc. resulted in a slight increase in yield and a slight decrease in levels of Se in plant; an increase in salinity from 0.5 to 3.0 dS/m resulted in a slight decrease in yield and a significant decrease in Se in plant	Greenhouse study; course grained silica sand; pH 6.5-7.0	Mikkelsen *et al.*, 1988
Alfalfa (***Medicago sativa***) L., Germain WL 512	1.0 mg/L as Na2SeO4	increase of B conc. resulted in a slight decrease in yield and a slight decrease in levels of Se in plant; an increase in salinity from 0.5 to 3.0 dS/m resulted in a slight decrease in yield and a significant decrease in Se in plant	Greenhouse study; course grained silica sand; pH 6.5-7.0	Mikkelsen *et al.*, 1988

Organism/species	Effect concentration for Se (dry wt basis) and Se species	Effect/ comments	Test conditions	Reference
Birdsfoot trefoil (***Lotus corniculatus***)	0.70 mg/kg in soil	60-d-Se conc. for whole plant was 3.1 mg/kg	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992
Birdsfoot trefoil (***Lotus corniculatus***)	0.70 mg/kg in soil	145-d-Se conc. for whole plant was 4.7 mg/kg	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992
Canola (***Brassica napus***)	0.70 mg/kg in soil	60-d-Se concs in leaves and stem were 51.0 and 9.1 mg/kg, respectively.	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992
Pea (***Pisum sativum*** L. cv. Fenomen)	5.0 umol as SeO4	21-d-relative growth rate was 6.3	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Pea (***Pisum sativum*** L. cv. Fenomen)	5.0 umol as combination of SeO4 and Cu	21-d-relative growth rate was -3.2	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Pea (***Pisum sativum*** L. cv. Fenomen)	5.0 umol as combination of SeO4 and Cd	21-d-relative growth rate was -4.5	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Pea (***Pisum sativum*** L. cv. Fenomen)	5.0 umol as SeO3	21-d-relative growth rate was 5.3	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Pea (***Pisum sativum*** L. cv. Fenomen)	5.0 umol as combination of SeO3 and Cu	21-d-relative growth rate was -3.4	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Pea (***Pisum sativum*** L. cv. Fenomen)	5.0 umol as combination of SeO3 and Cd	21-d-relative growth rate was -5.3	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Tall fescue ***(Festuca arundinacea)***	0.70 mg/kg in soil	60-d-Se conc. for whole plant was 1.3 mg/kg	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992
Tall fescue ***(Festuca arundinacea)***	0.70 mg/kg in soil	145-d-Se conc. for whole plant was 1.5 mg/kg	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992

Organism/species	Effect concentration for Se (dry wt basis) and Se species	Effect/ comments	Test conditions	Reference
Wheat (*Triticum aestivum* L. cv. Fenomen)	5.0 umol as SeO4	21-d-relative growth rate was-3.4	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Wheat (*Triticum aestivum* L. cv. Fenomen)	5.0 umol as combination of SeO4 and Cu	21-d-relative growth rate was -4.1	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Wheat (*Triticum aestivum* L. cv. Fenomen)	5.0 umol as combination of SeO4 and Cd	21-d-relative growth rate was -6.6	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Wheat (*Triticum aestivum* L. cv. Fenomen)	5.0 umol as SeO3	21-d-relative growth rate was -2.7	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Wheat (*Triticum aestivum* L. cv. Fenomen)	5.0 umol as combination of SeO3 and Cu	21-d-relative growth rate was -3.6	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Wheat (*Triticum aestivum* L. cv. Fenomen)	5.0 umol as combination of SeO3 and Cd	21-d-relative growth rate was -5.6	pH 6.0; temp. 27° during day and 21° at night; relative humididty was 70-80%	Landberg and Greger, 1994
Wild brown mustard (*Brassica juncea*)	2.0 mg Se/L as Na2SeO4	40-d study (with 3.0 dS/m of salt and 3.0 mg/L of Boron) shoot wts were 13.6 g fresh, 1.7 g dry and root wet wts were 6.6 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	6.0 mg Se/L as Na2SeO4	40-d study (with 3.0 dS/m of salt and 3.0 mg/L of Boron) shoot wts were 12.7 g fresh, 1.5 g dry and root wet wts were 5.9 g fresh and 0.3 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	15.0 mg Se/L as Na2SeO4	40-d study (with 3.0 dS/m of salt and 3.0 mg/L of Boron) shoot wts were 14.4 g fresh, 1.9 g dry and root wet wts were 6.2 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990

Organism/species	Effect concentration for Se (dry wt basis) and Se species	Effect/ comments	Test conditions	Reference
Wild brown mustard (***Brassica juncea***)	2.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 3.0 mg/L of Boron) shoot wts were 15.0 g fresh, 2.1 g dry and root wet wts were 7.1 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (***Brassica juncea***)	6.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 3.0 mg/L of Boron) shoot wts were 13.2 g fresh, 2.0 g dry and root wet wts were 6.3 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (***Brassica juncea***)	15.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 3.0 mg/L of Boron) shoot wts were 16.0 g fresh, 2.1 g dry and root wet wts were 6.4 g fresh and 0.5 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (***Brassica juncea***)	2.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 15.4 g fresh, 1.8 g dry and root wet wts were 5.4 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (***Brassica juncea***)	6.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 15.8 g fresh, 1.9 g dry and root wet wts were 6.0 g fresh and 0.5 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (***Brassica juncea***)	15.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 14.9 g fresh, 1.6 g dry and root wet wts were 5.3 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (***Brassica juncea***)	2.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 15.0 mg/L of Boron) shoot wts were 15.9 g fresh, 2.2 g dry and root wet wts were 5.6 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990

Organism/species	Effect concentration for Se (dry wt basis) and Se species	Effect/ comments	Test conditions	Reference
Wild brown mustard (*Brassica juncea*)	2.0 mg Se/L as Na2SeO4	40-d study (with 15.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 15.4 g fresh, 1.8 g dry and root wet wts were 5.4 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	6.0 mg Se/L as Na2SeO4	40-d study (with 15.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 15.8 g fresh, 1.9 g dry and root wet wts were 6.0 g fresh and 0.5 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	15.0 mg Se/L as Na2SeO4	40-d study (with 15.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 14.9 g fresh, 1.6 g dry and root wet wts were 5.3 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	2.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 15.0 mg/L of Boron) shoot wts were 15.6 g fresh, 2.0 g dry and root wet wts were 5.9 g fresh and 0.4 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	2.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 15.0 mg/L of Boron) shoot wts were 13.9 g fresh, 1.4 g dry and root wet wts were 4.4 g fresh and 0.3 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	15.0 mg Se/L as Na2SeO4	40-d study (with 10.0 dS/m of salt and 10.0 mg/L of Boron) shoot wts were 14.7 g fresh, 1.7 g dry and root wet wts were 4.9 g fresh and 0.3 g dry	In greenhouse water cultures; pH 6.5-7; temp. 21° during the day and 18° at night	Banuelos *et al.*, 1990
Wild brown mustard (*Brassica juncea*)	0.70 mg/kg in soil	60-d Se-concs in whole plant, leaves and stem were 34.1, 50.0 and 8.3 mg/kg, respectively.	Field study; temp. 27° during the day and 15° at night	Banuelos *et al.*, 1992

Table 12.01 : Effect of Selenium on livestock

Species	Effect concentration for Se (dry wt basis) and Se species	Effect/comments	Test conditions	Reference
calves	2.0 mg Se/kg body weight of calf, administered by injection	12-h-lassitude, inappetance, dyspnea and death	neonatal calves were tested	MacDonald *et al.*, 1981
calves	20.0 mg Se/kg body weight administered orally	6.0-h-death	-	Dudley, 1936
calves	9.9-11.0 mg Se/kg body weight administered orally	lethal dose	-	Miller and Williams, 1940
chicken	5.0 ug Se/g in diet	LOAEC	-	Ort and Latshaw, 1978
cow	10.0 ppm supplemented in diet	conc. in cows reached only 0.275 mg Se/L in blood serum due possibly to the ruminal microbial populations and environment	-	Ellis *et a* l., 1989
horses	20.0 ppm in hay diet	3-wk-single serum sample of one of 25 affected horses was 0.928 mg Se/L and was reduced to 0.525 after high Se diet had been discontinued and after 6 wks the mean serum value of three horses was 0.285	-	Stowe and Herdt, 1992
pigs	8.81 ppm in feed	5-wk-conc in one of pigs after 5 wks was 1.525 mg Se/L, pigs developed an uncoordinated gait and/or varying degrees of parensis; 1 wk after high Se diet discontinued levels were between .451 and 1.488 of 13 pigs tested and after 4 wks. .258 in 9 pigs	-	Stowe and Herdt, 1992
pigs	2.0 mg Se/kg body weight of pig, administered by injection	4-h:-100% mortality	-	Orstadins, 1960

Species	Effect concentration for Se (dry wt basis) and Se species	Effect/comments	Test conditions	Reference
pigs	1.2 mg Se/kg body weight of pig, administered by injection	5-h-100% mortality	-	Orstadins, 1960
sheep	3.0 as Na2SeO3 ug Se/g in diet	10-d-tissue conc. of ug Se/g were: 1.89 in liver, 6.9 in kidney, 0.52 in muscle, 1.31 in heart, 2.35 in spleen and 0.12 (mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	3.0 as Na2SeO3 ug Se/g in diet	20-d-tissue conc. of ug Se/g were: 2.30 in liver, 7.5 in kidney, 0.51 in muscle, 1.33 in heart, 2.28 in spleen and 0.12 (mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	3.0 as Na2SeO3 ug Se/g in diet	30-d-tissue conc. of ug Se/g were: 3.79 in liver, 8.2 in kidney, 0.48 in muscle, 1.21 in heart, 2.36 in spleen and 0.13 (in mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	6.0 as Na2SeO3 ug Se/g in diet	10-d-tissue conc. of ug Se/g were: 5.86 in liver, 11.5 in kidney, 0.56 in muscle, 1.47 in heart, 3.09 in spleen and 0.17 (mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	6.0 as Na2SeO3 ug Se/g in diet	20-d-tissue conc. of ug Se/g were: 5.45 in liver, 12.0 in kidney, 0.56 in muscle, 1.57 in heart, 2.97 in spleen and 0.18 (in mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	6.0 as Na2SeO3 ug Se/g in diet	30-d-tissue conc. of ug Se/g were: 7.21 in liver, 11.8 in kidney, 0.55 in muscle, 1.48 in heart, 3.05 in spleen and 0.19 (in mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	9.0 as Na2SeO3 ug Se/g in diet	10-d- tissue conc. of ug Se/g were: 8.31 in liver, 14.7 in kidney, 0.66 in muscle, 1.61 in heart, 3.08 in spleen and 0.24 (in mg Se/L) in serum	-	Echevarria *et al.*, 1988

Species	Effect concentration for Se (dry w basis) and Se species	Effect/comments	Test conditions	Reference
sheep	9.0 as Na2SeO3 ug Se/g in diet	20-d-tissue conc. of ug Se/g were: 8.12 in liver, 14.4 in kidney, 0.67 in muscle, 1.65 in heart, 3.12 in spleen and 0.25 (in mg Se/L) in serum	-	Echevarria *et al.*, 1988
sheep	9.0 as Na2SeO3 ug Se/g in diet	30-d-tissue conc. of ug Se/g were: 8.47 in liver, 15.3 in kidney, 0.70 in muscle, 1.69 in heart, 3.12 in spleen and 0.27 (in mg Se/L) in serum	-	Echevarria *et al.*, 1988
KEY				
LOAEC = Lowest Observed Adverse Effect Concentration				

Figure 9.01: Se toxicity (acute) to freshwater fish

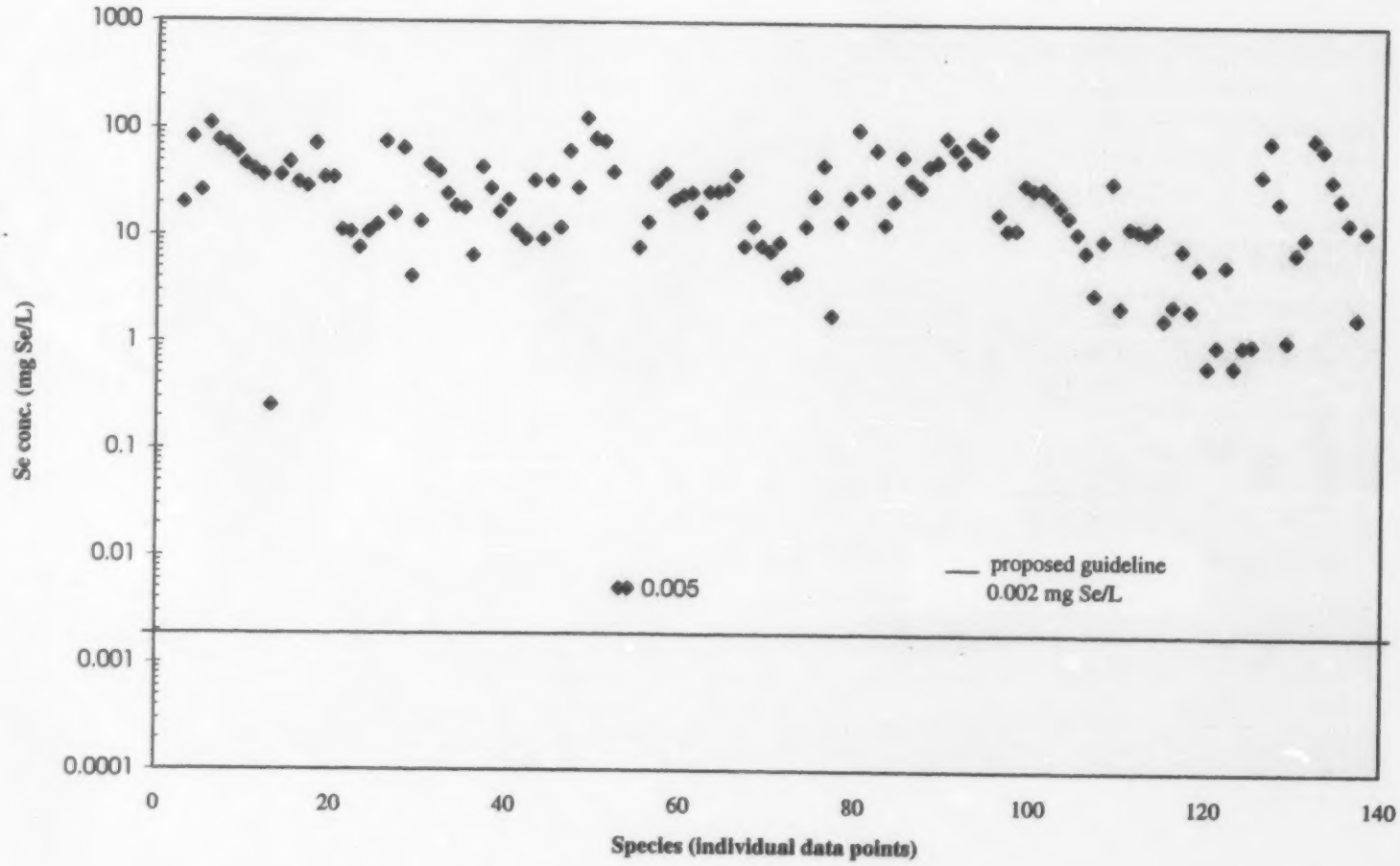

Figure 9.02: Se toxicity (acute) to different species of freshwater fish

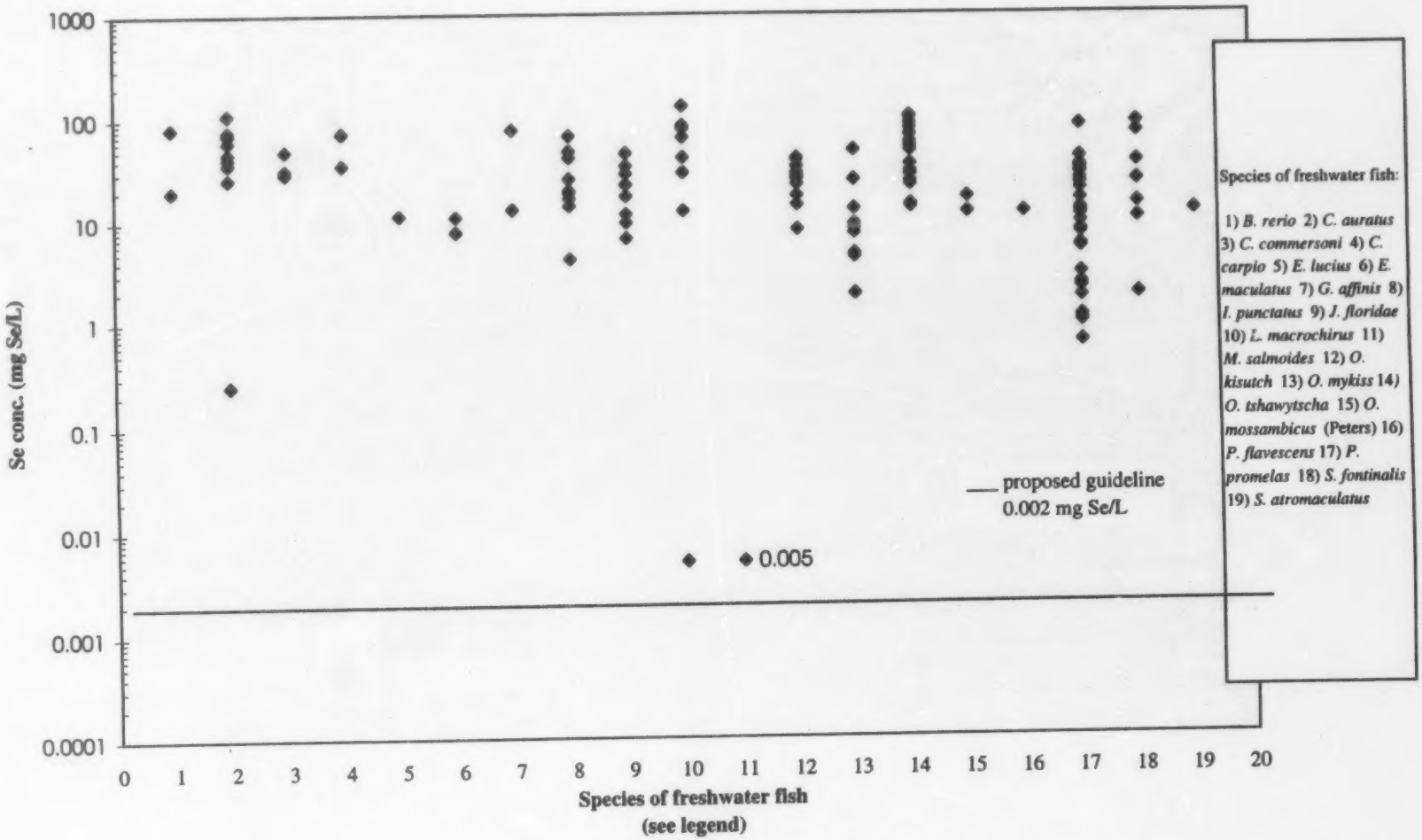
1000
100
10
1
0.1
0.01
0.001
0.0001
Se conc. (mg Se/L)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Species of freshwater fish
(see legend)
proposed guideline
0.002 mg Se/L
0.005
Species of freshwater fish:
1) B. rerio 2) C. auratus 3) C. commersoni 4) C. carpio 5) E. lucius 6) E. maculatus 7) G. affinis 8) I. punctatus 9) J. floridae 10) L. macrochirus 11) M. salmoides 12) O. kisutch 13) O. mykiss 14) O. tshawytscha 15) O. mossambicus (Peters) 16) P. flavescens 17) P. promelas 18) S. fontinalis 19) S. atromaculatus

Figure 9.03: Se toxicity (96-h LC_{50}) to freshwater fish

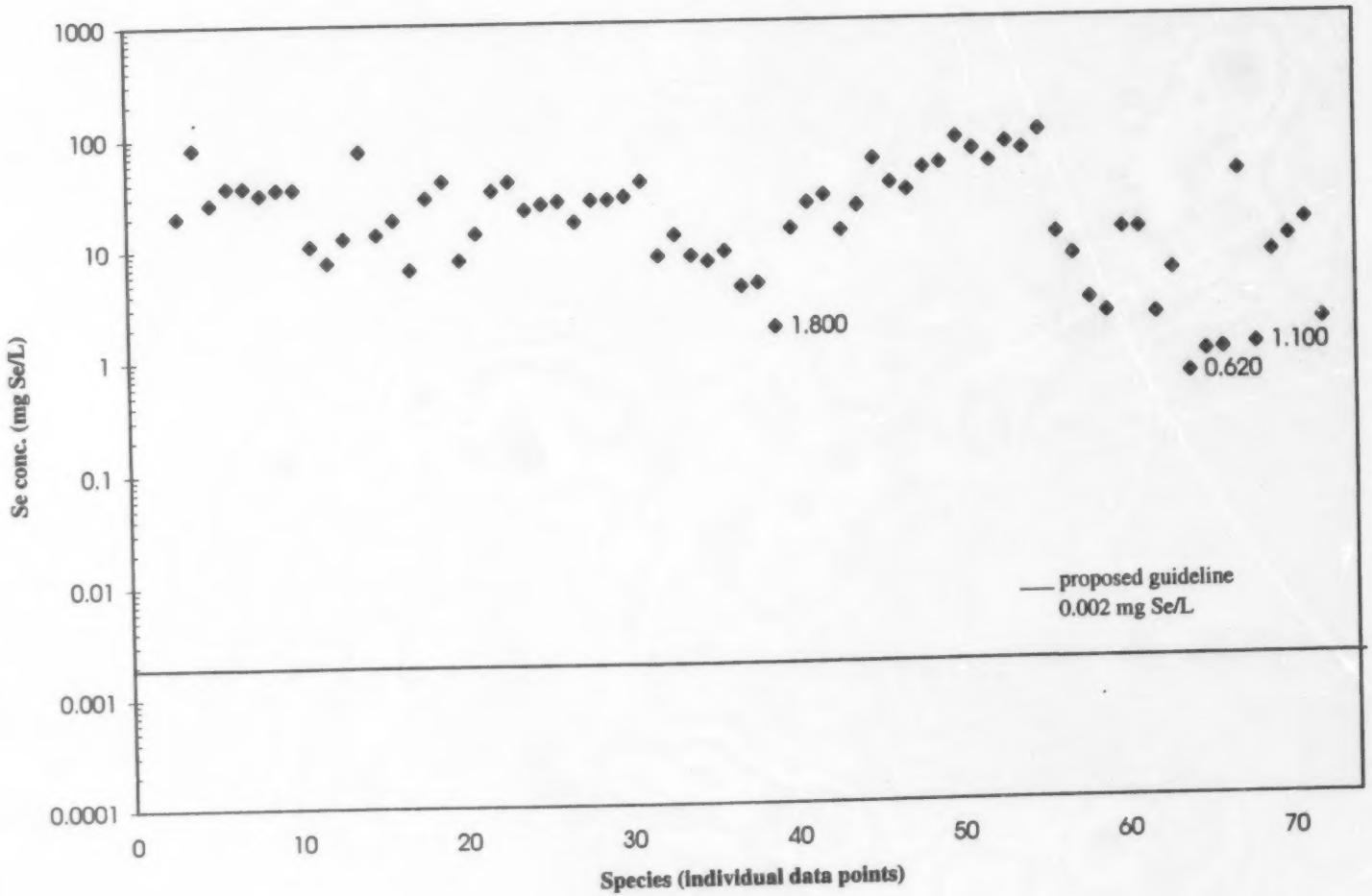

Figure 9.04: Se toxicity (96-h LC_{50}) to freshwater fish vs Se species

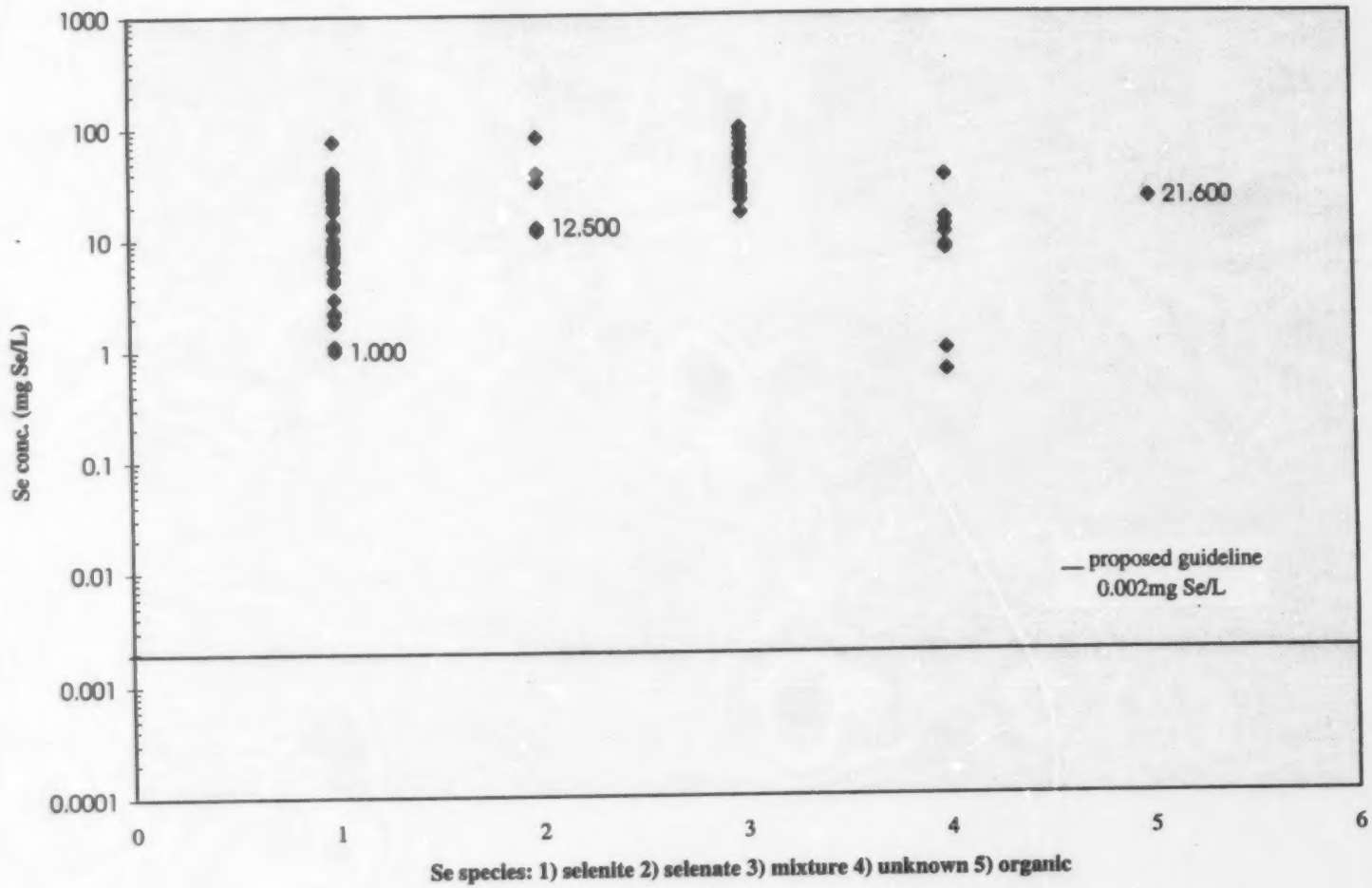

Figure 9.05: Se toxicity (chronic) to freshwater fish

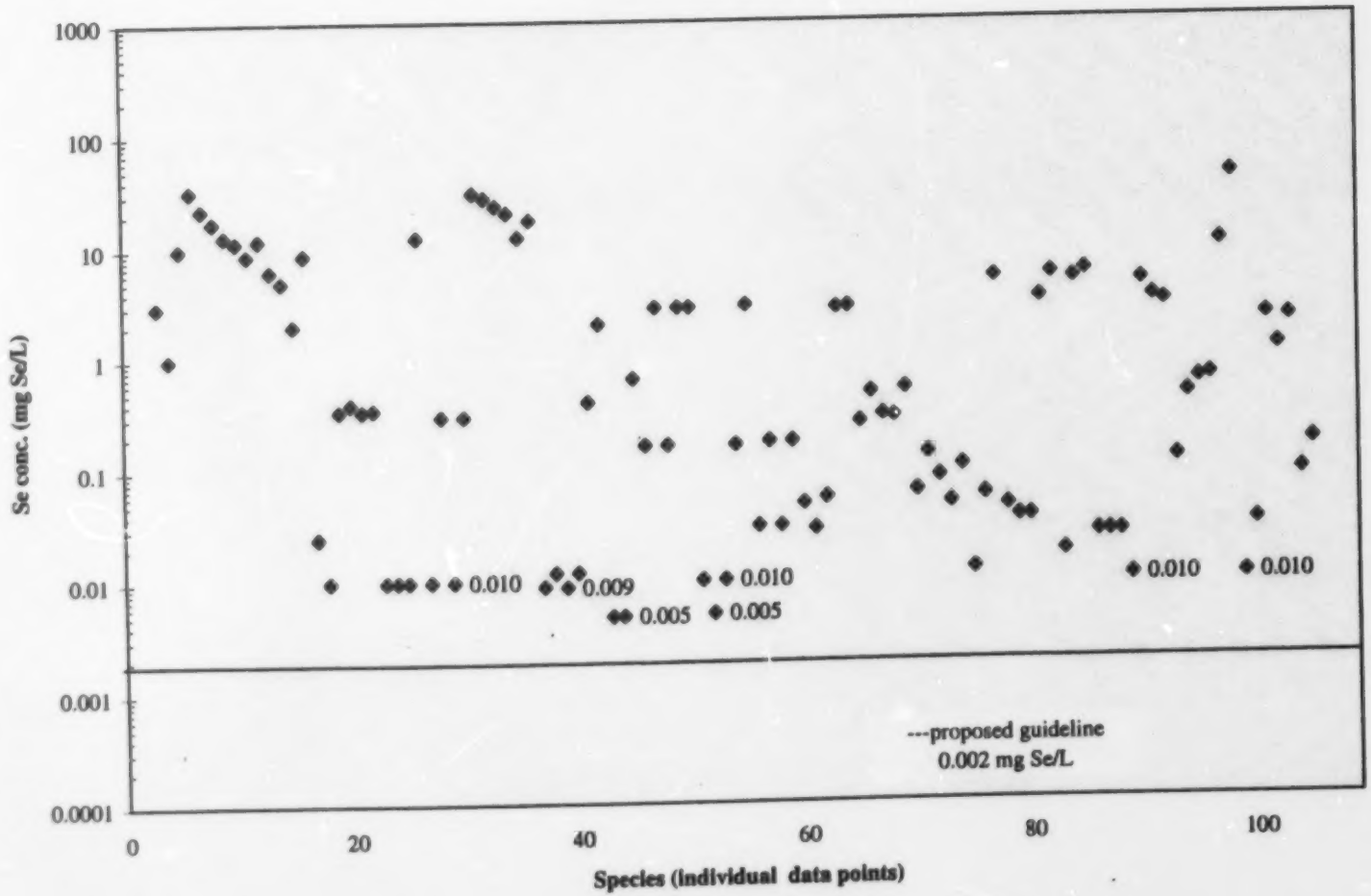

Figure 9.06: Se toxicity (chronic) to different species of freshwater fish

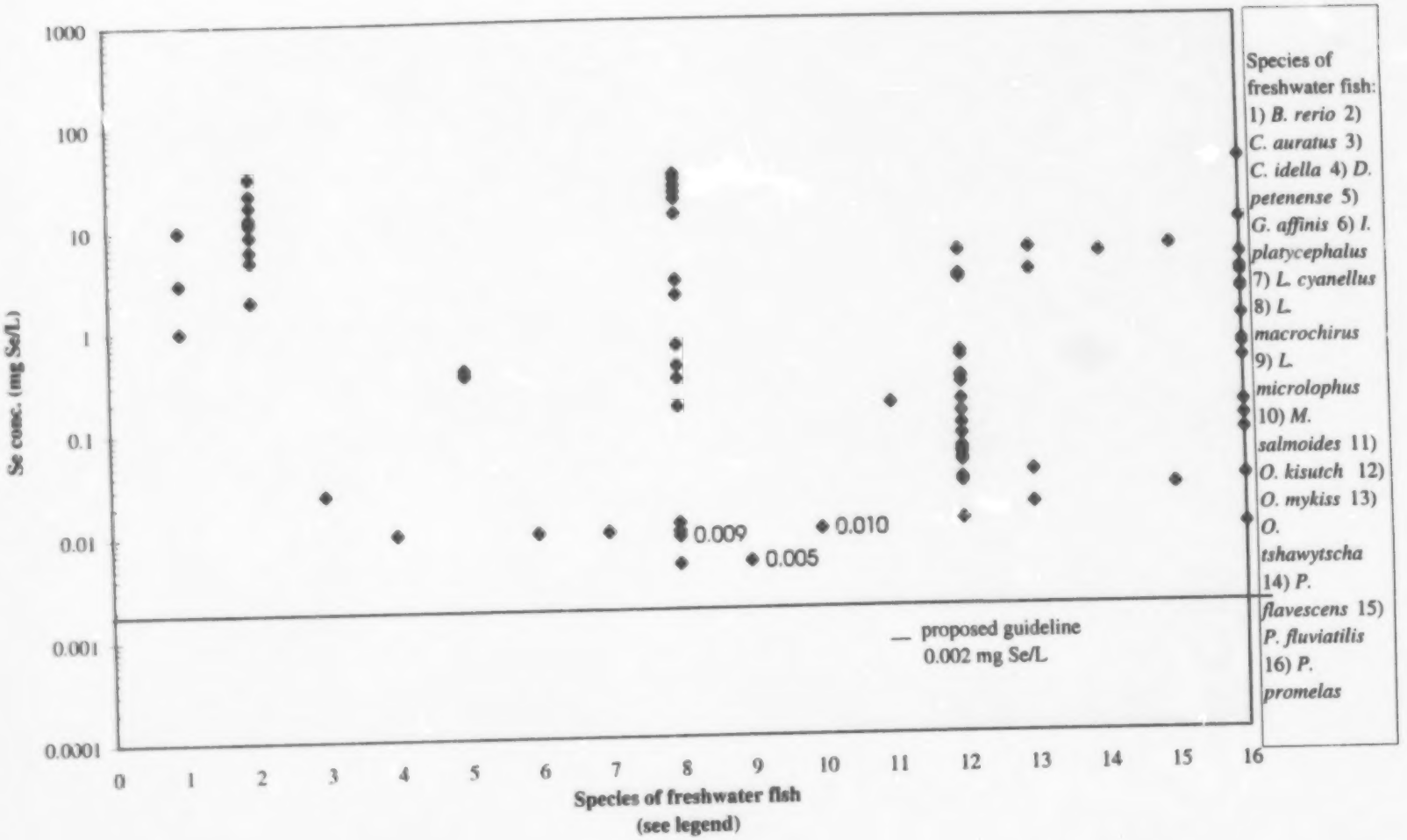
1000
100
10
1
0.1
0.01
0.001
0.0001
Se conc. (mg Se/L)
0.009
0.010
0.005
proposed guideline
0.002 mg Se/L
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Species of freshwater fish
(see legend)
Species of freshwater fish:
1) B. rerio 2) C. auratus 3) C. idella 4) D. petenense 5) G. affinis 6) I. platycephalus 7) L. cyanellus 8) L. macrochirus 9) L. microlophus 10) M. salmoides 11) O. kisutch 12) O. mykiss 13) O. tshawytscha 14) P. flavescens 15) P. fluviatilis 16) P. promelas

Figure 9.07: Se toxicity (chronic) to freshwater fish vs Se species

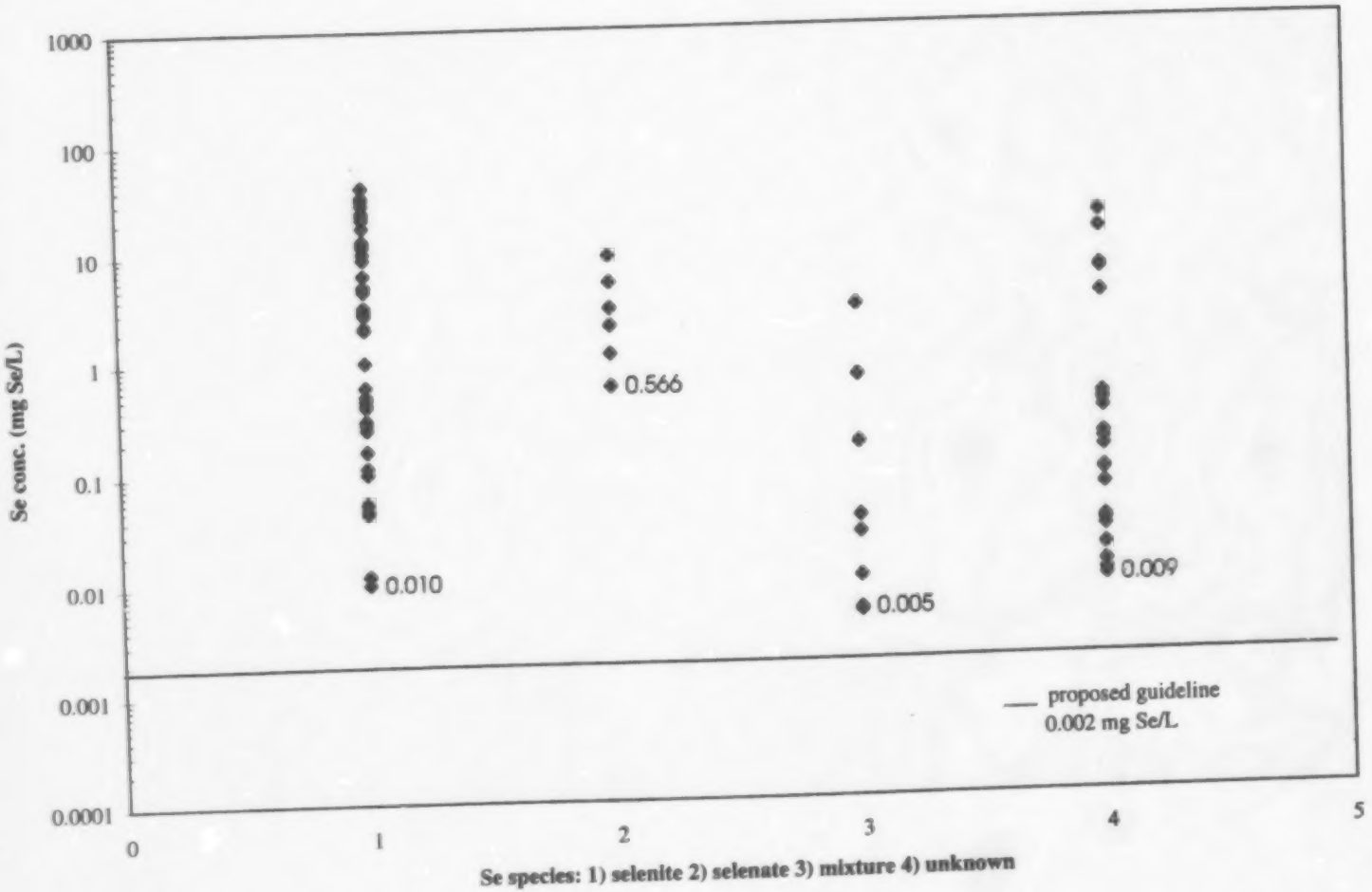

Figure 9.08: Se toxicity (acute) to freshwater invertebrates

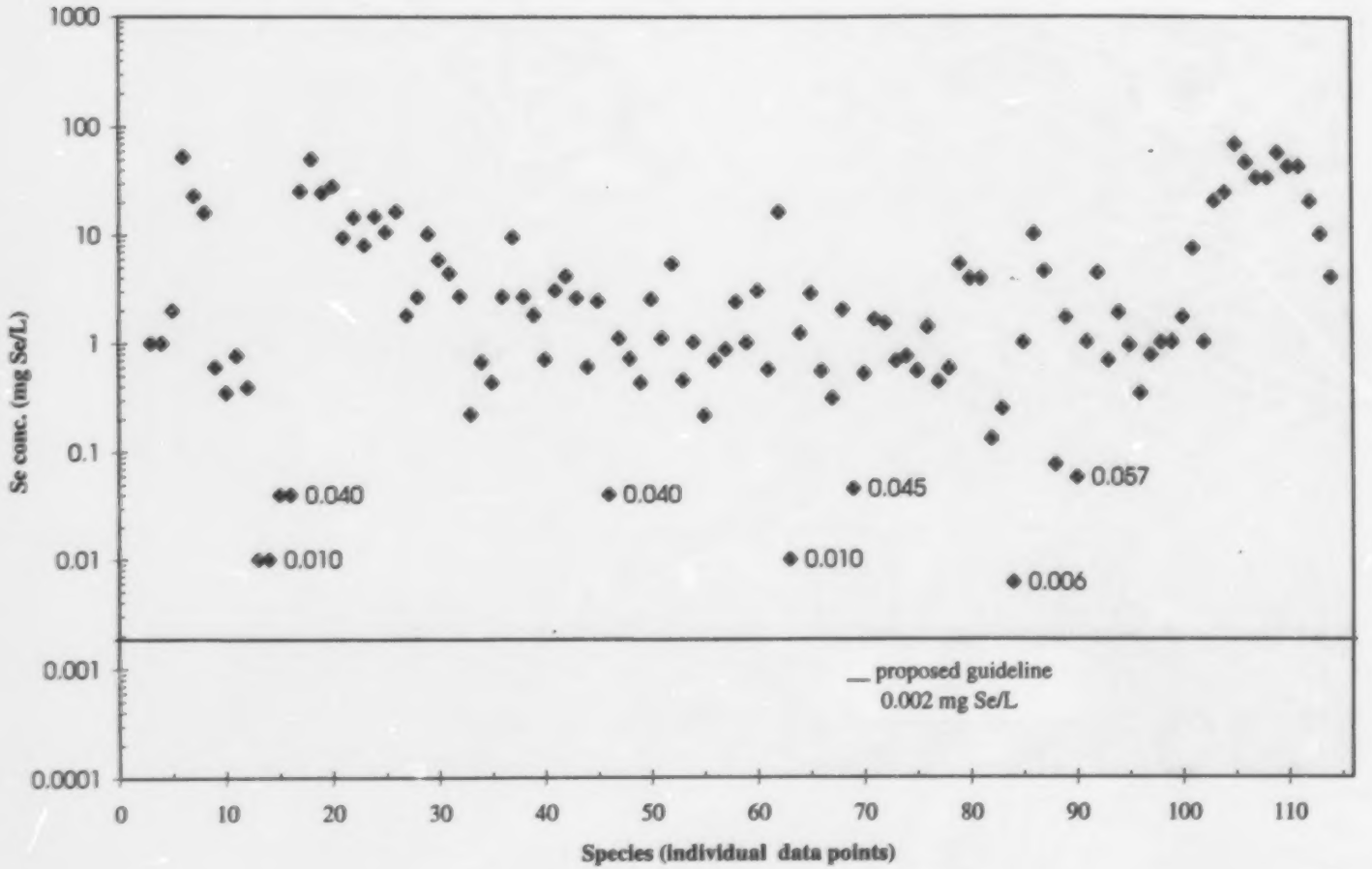

Figure 9.09: Se toxicity (acute) to different species of freshwater invertebrates

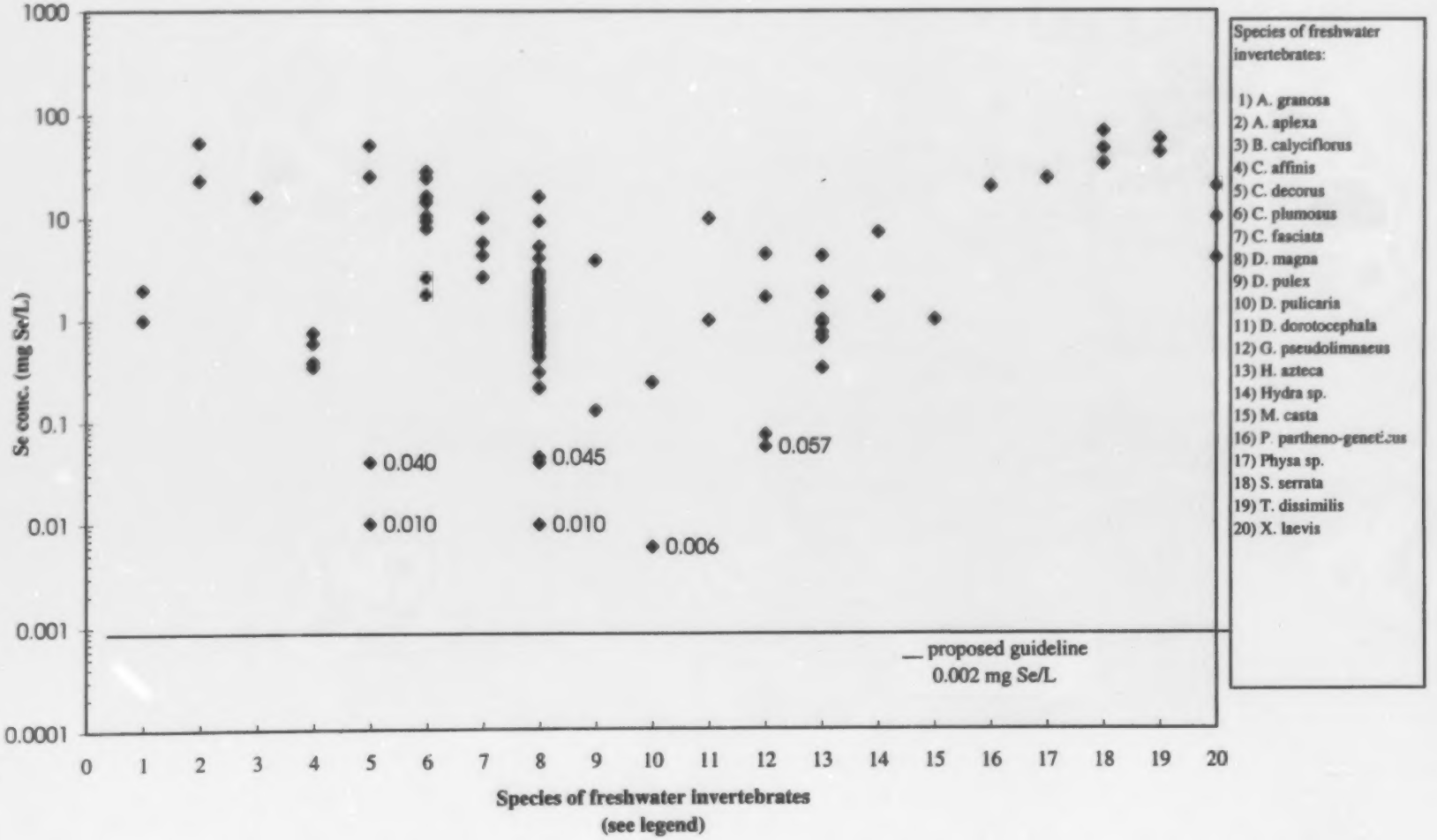

Figure 9.10: Se toxicity (96-h LC_{50}) to freshwater invertebrates

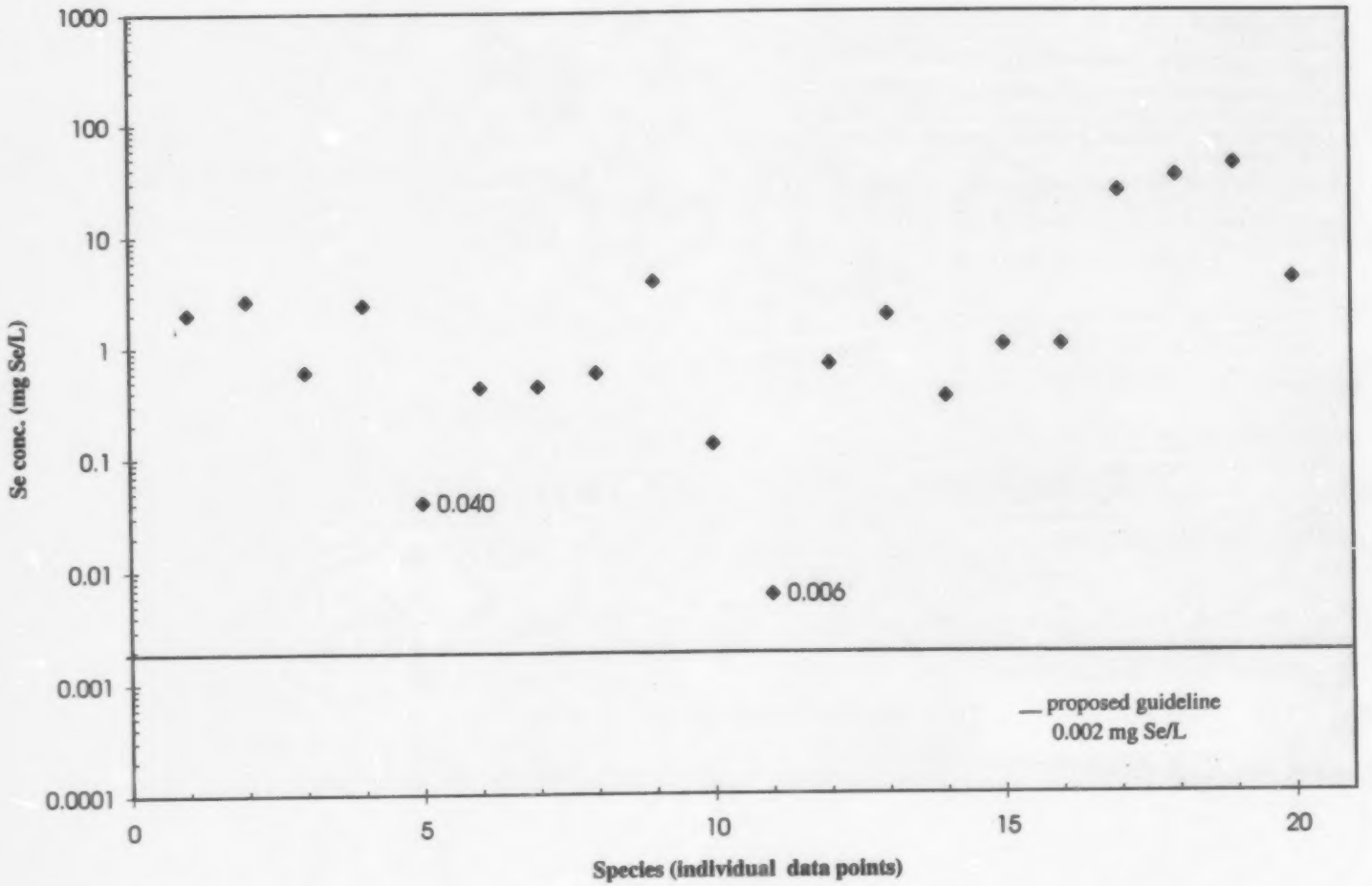

Figure 9.11: Se toxicity (96-h LC_{50}) to fresh water invertebrates vs Se species

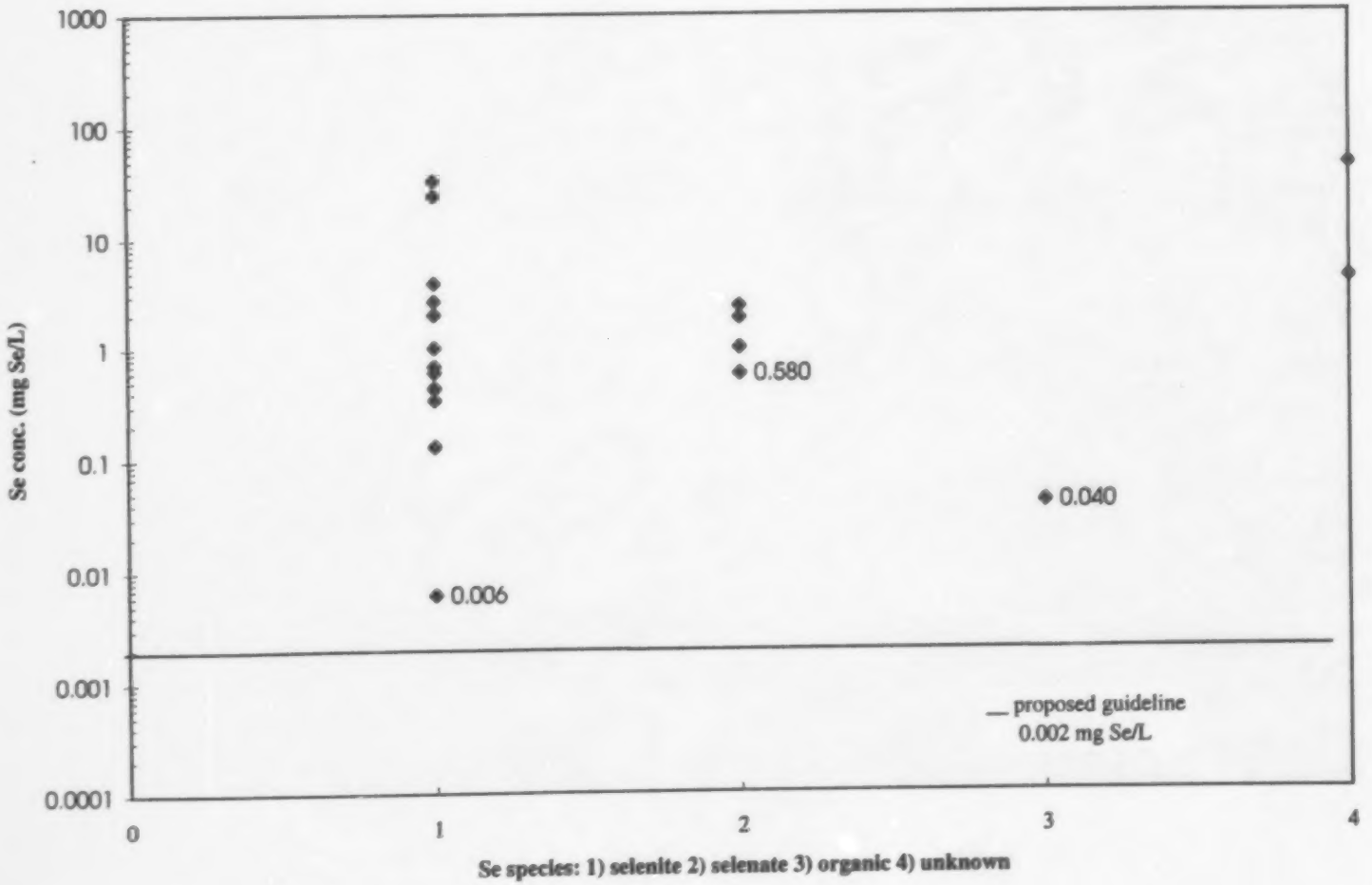

Figure 9.12: Se toxicity (chronic) to freshwater invertebrates

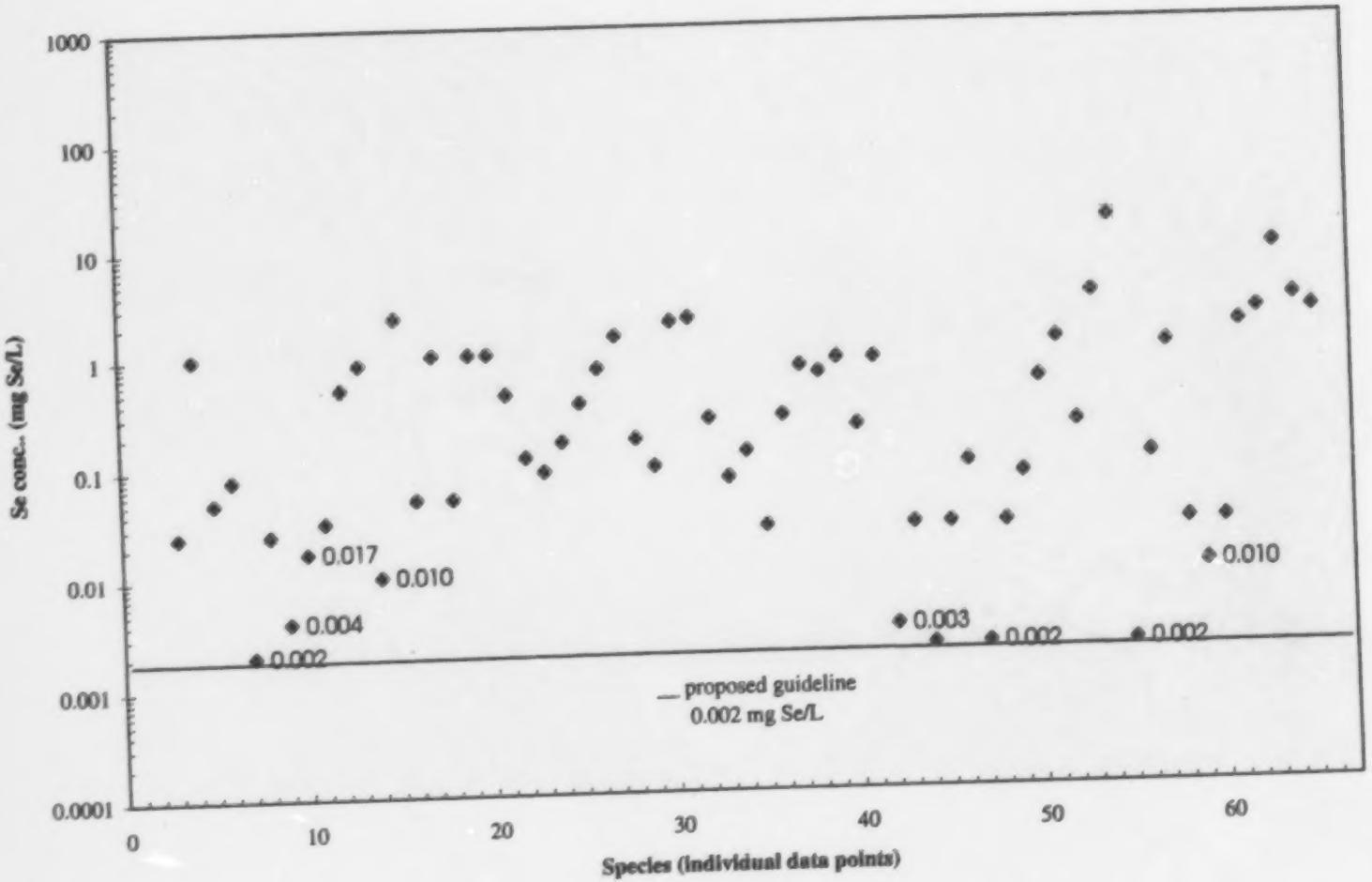

Figure 9.13: Se toxicity (chronic) to different species of freshwater invertebrates

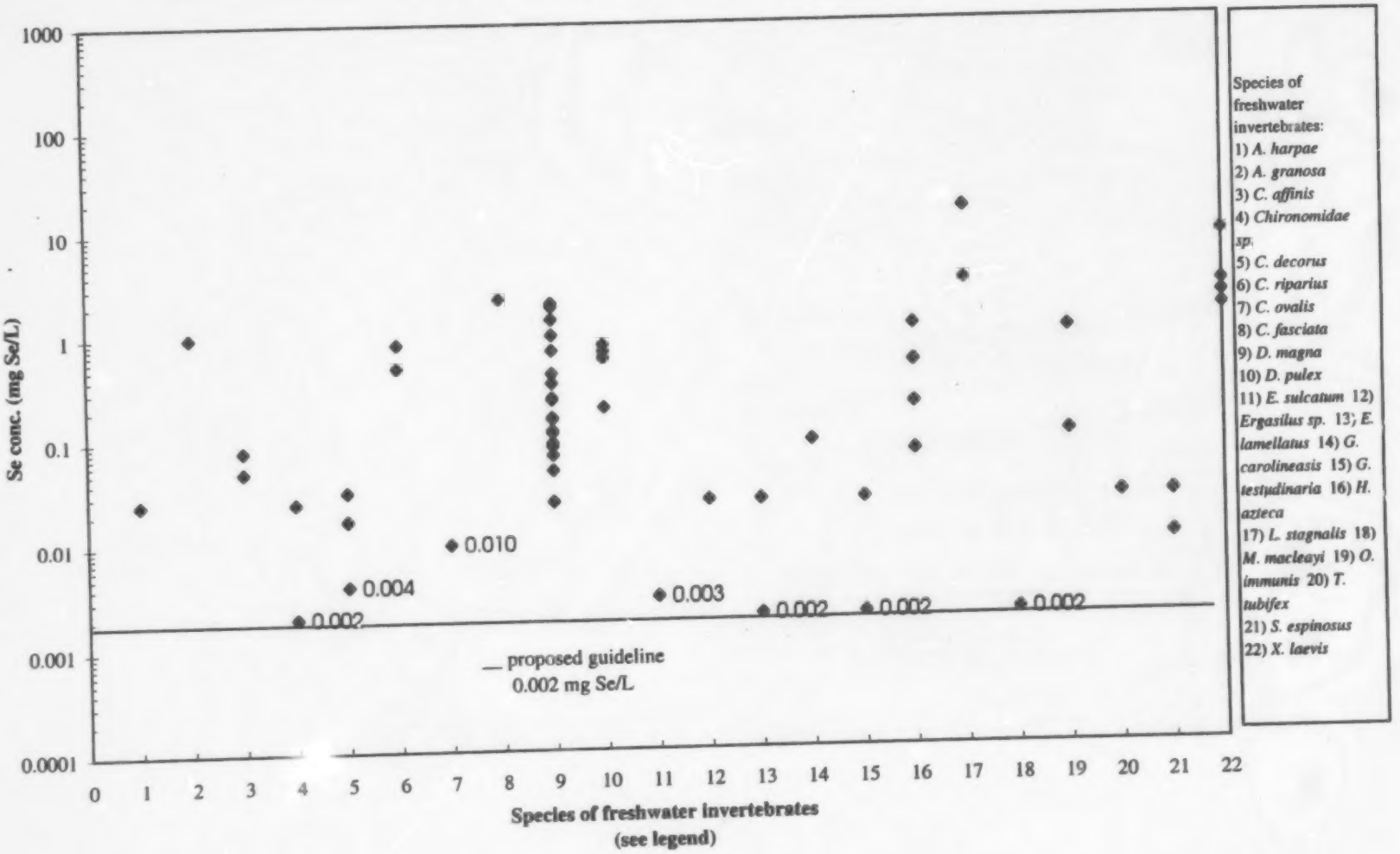

Figure 9.14: Se toxicity (chronic) to freshwater invertebrates vs Se species

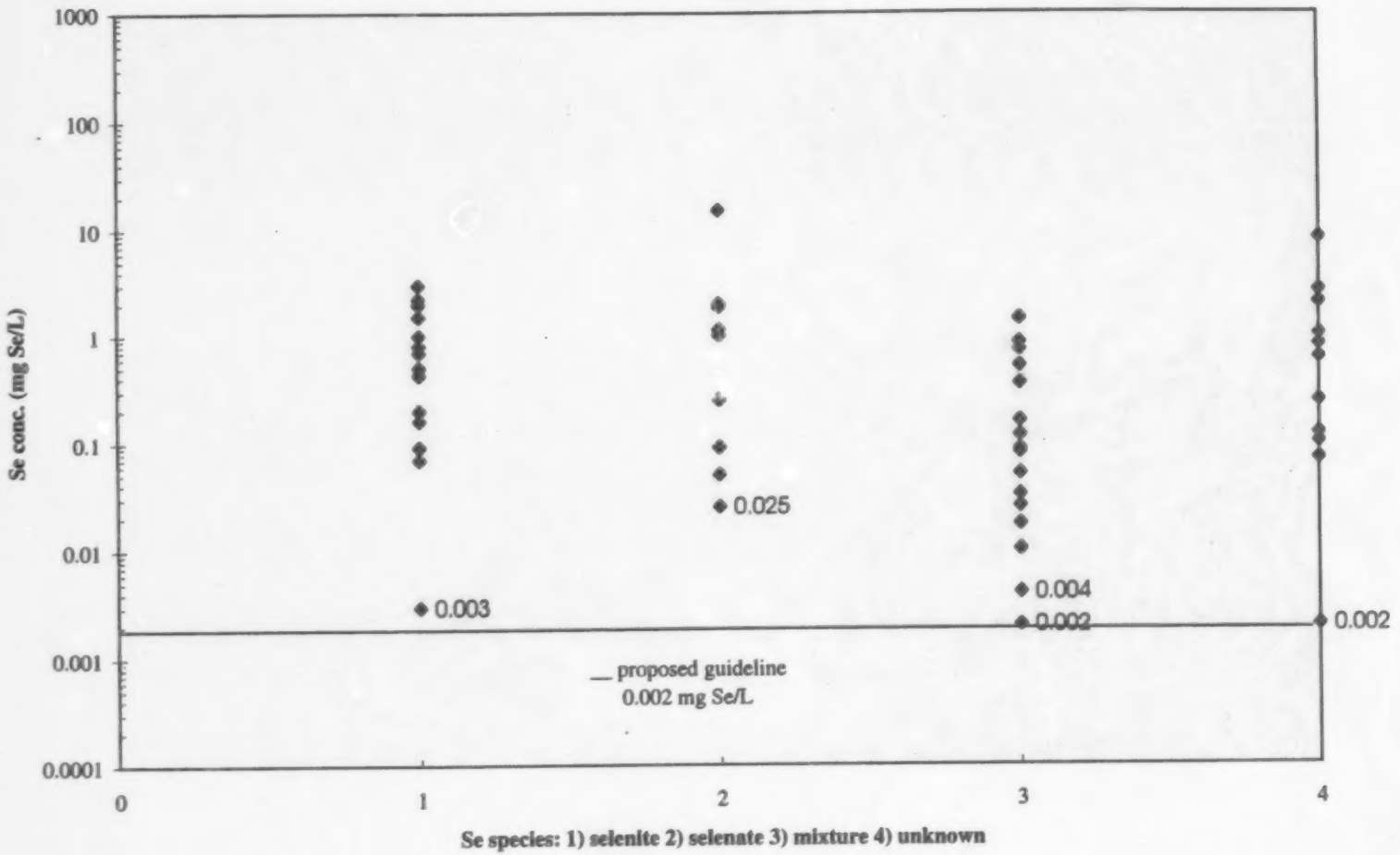

Figure 9.16: Se toxicity to different species of freshwater algae and macrophytes

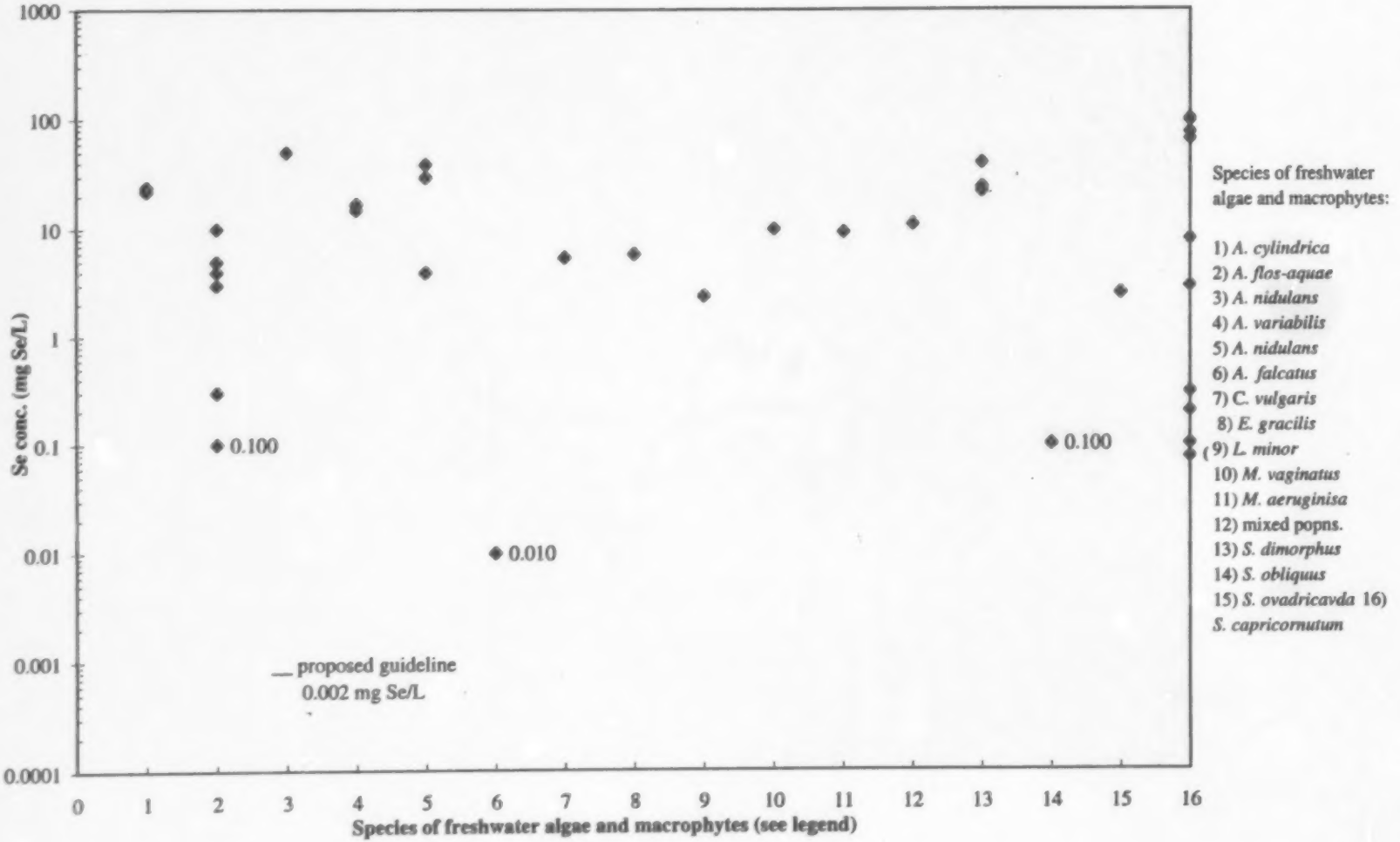

Figure 9.17: Se toxicity to freshwater algae and macrophytes vs Se species

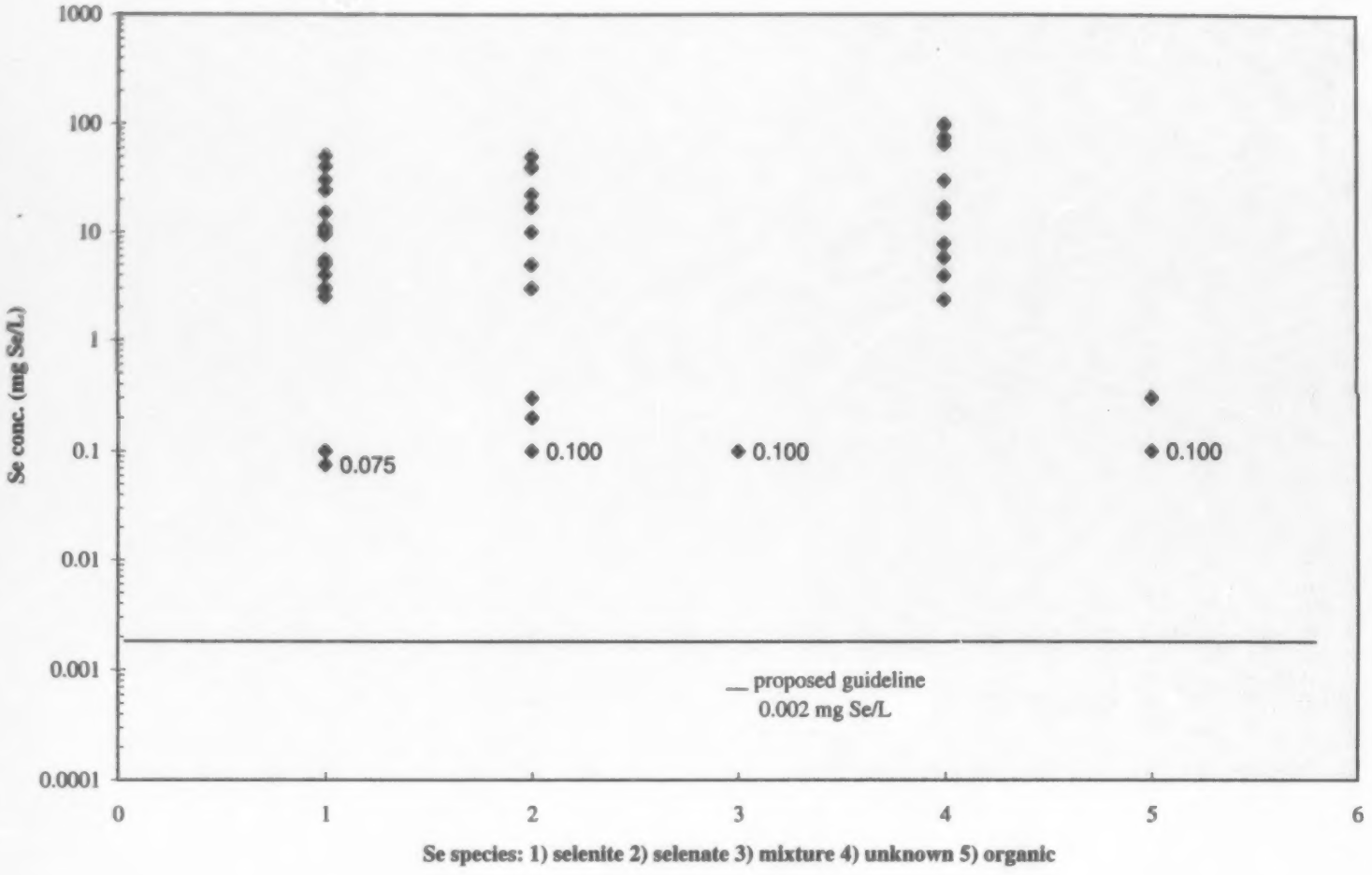

Figure 9.18: Se toxicity to marine fish

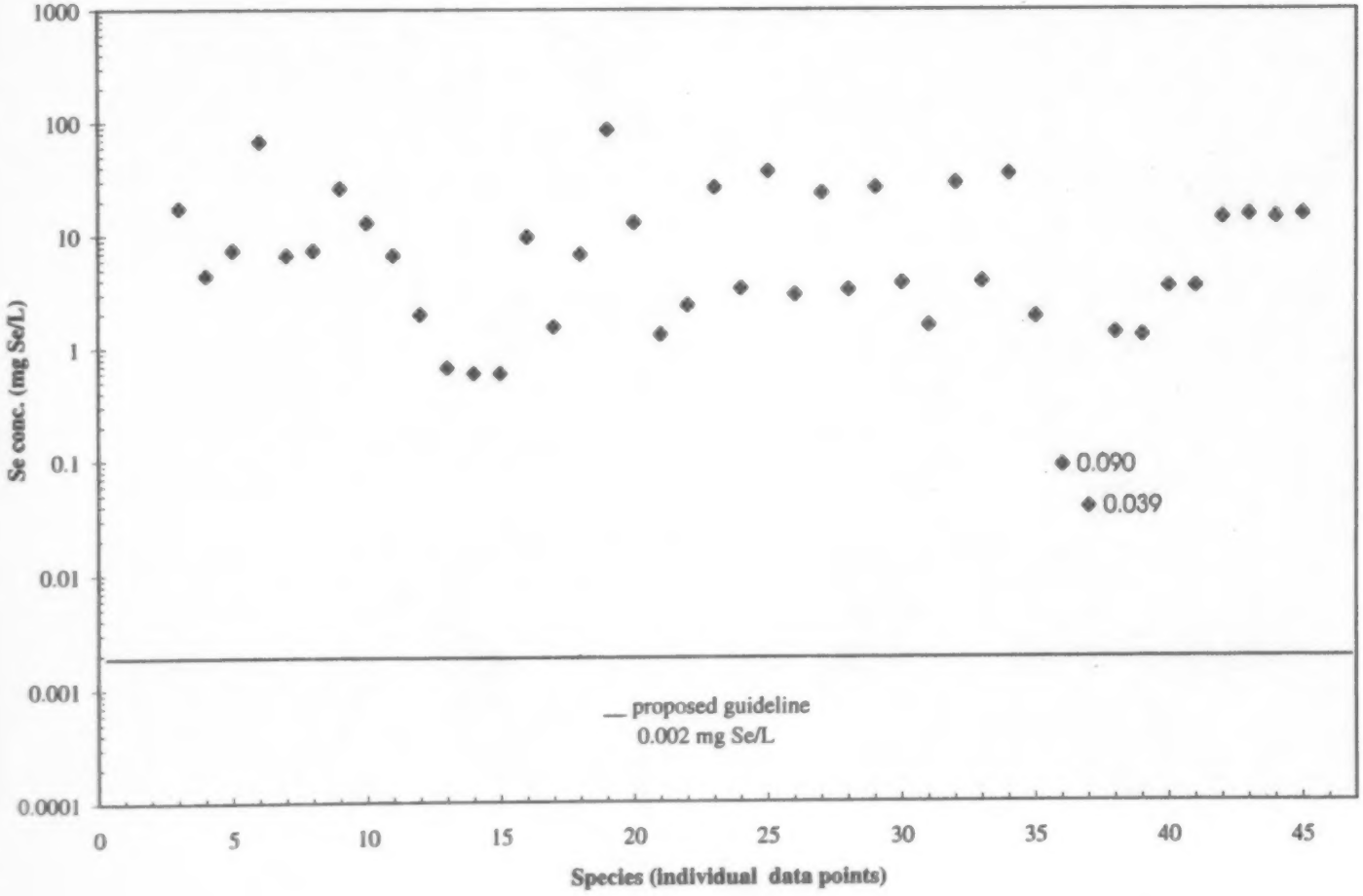

Figure 9.19: Se toxicity to different species of marine fish

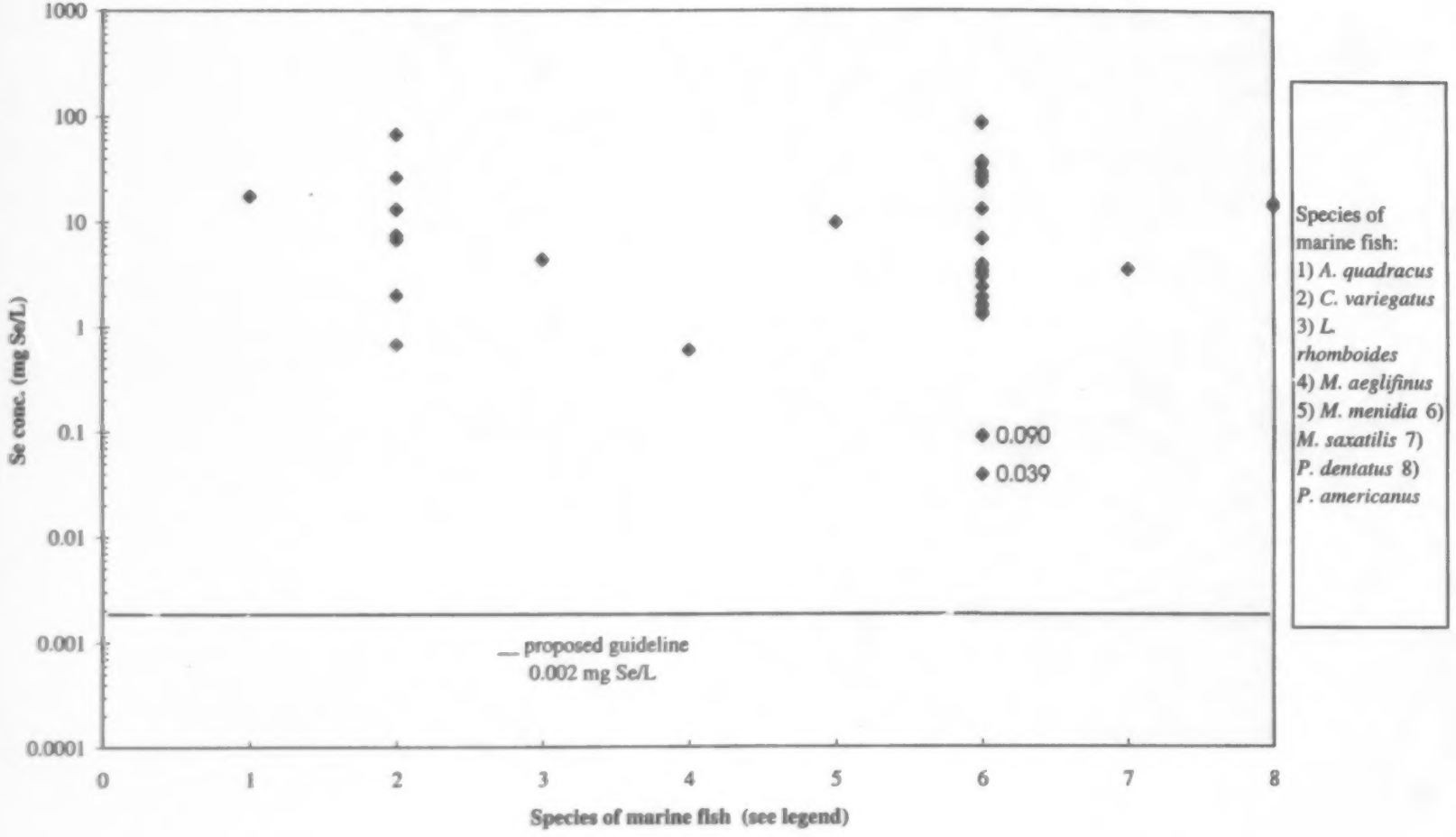

Figure 9.20: Se toxicity (96-h LC_{50}) to marine fish

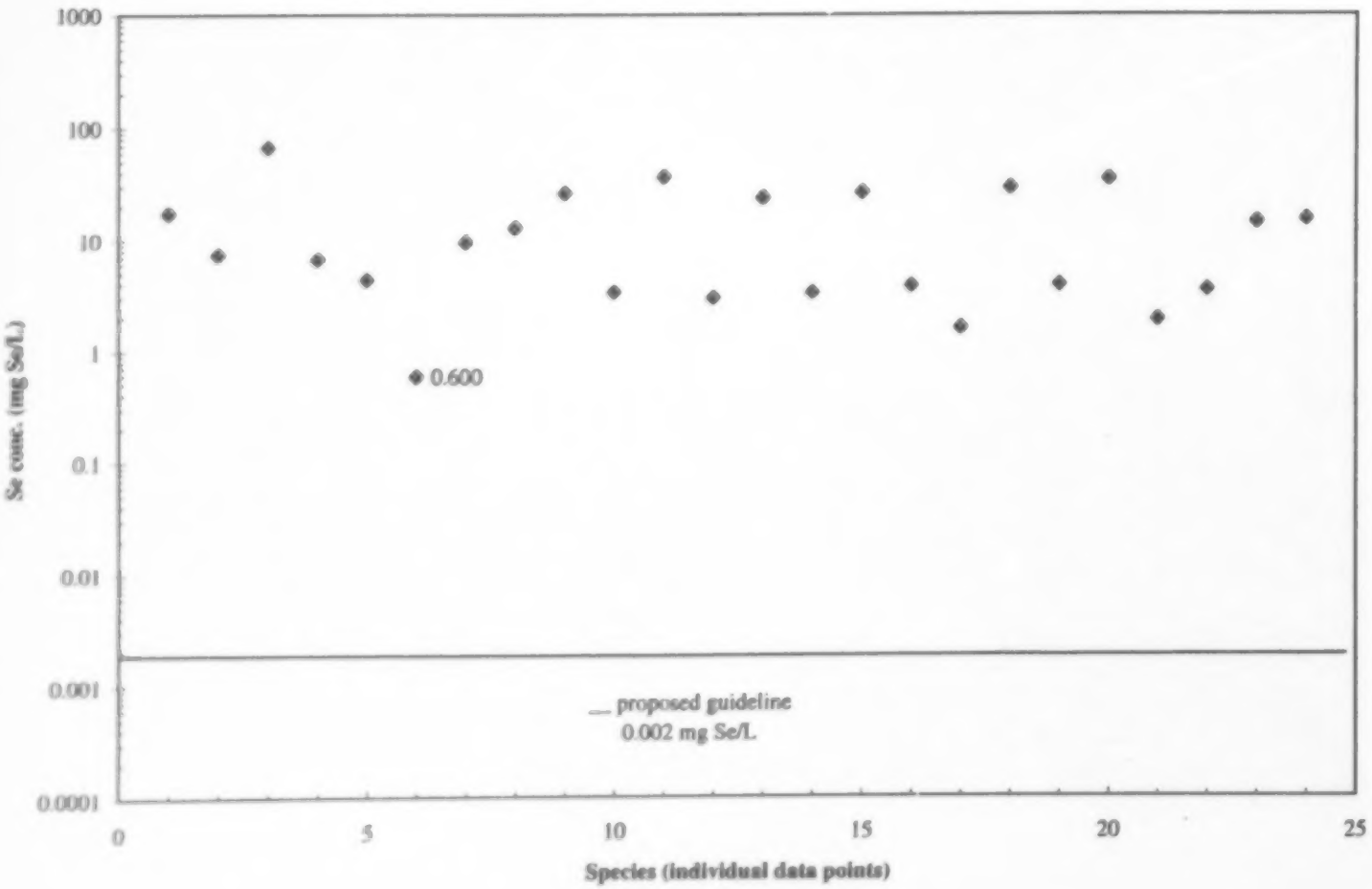

Figure 9.21: Se toxicity (96-h LC_{50}) to marine fish vs Se species

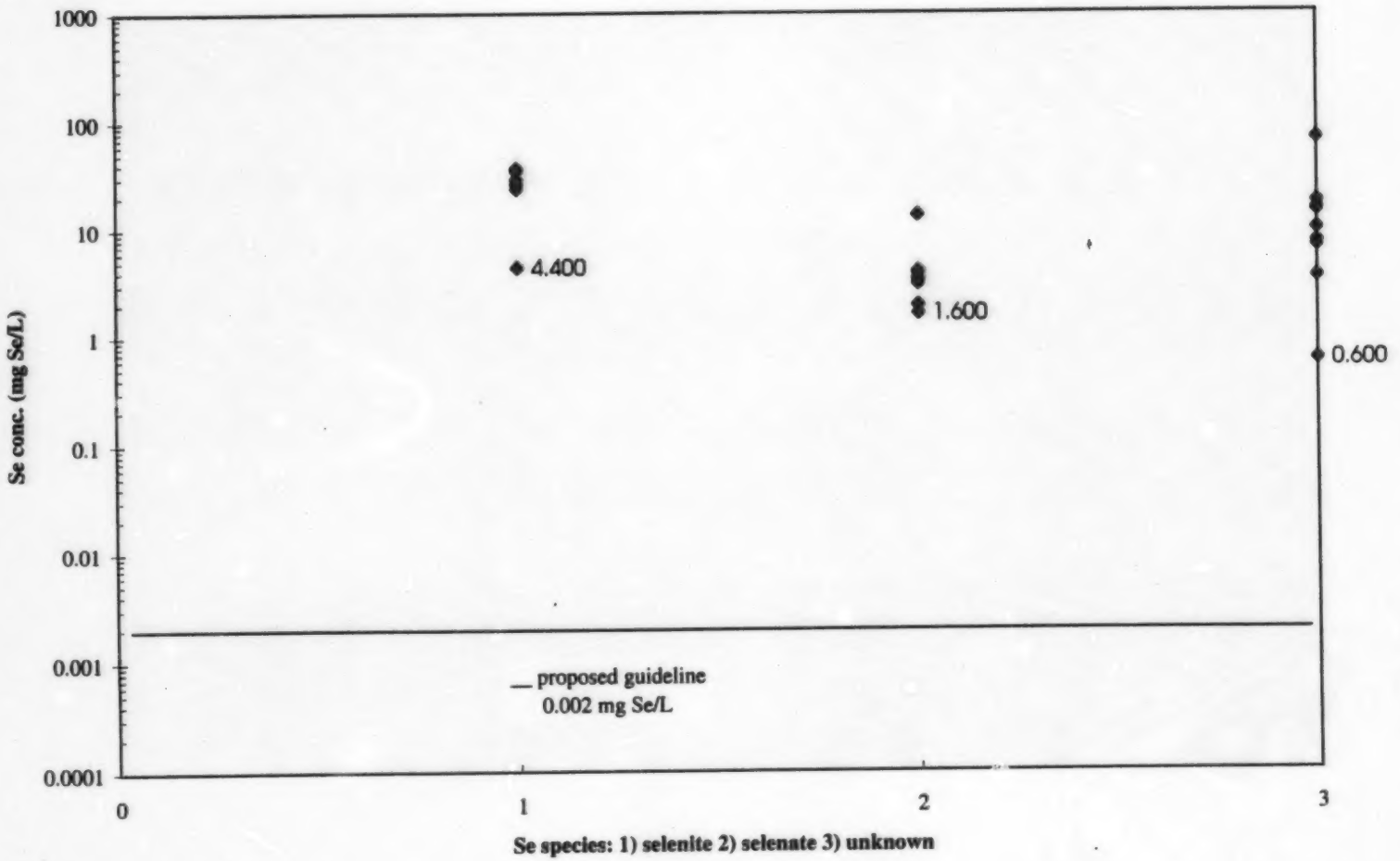

Figure 9.22: Se toxicity to marine invertebrates

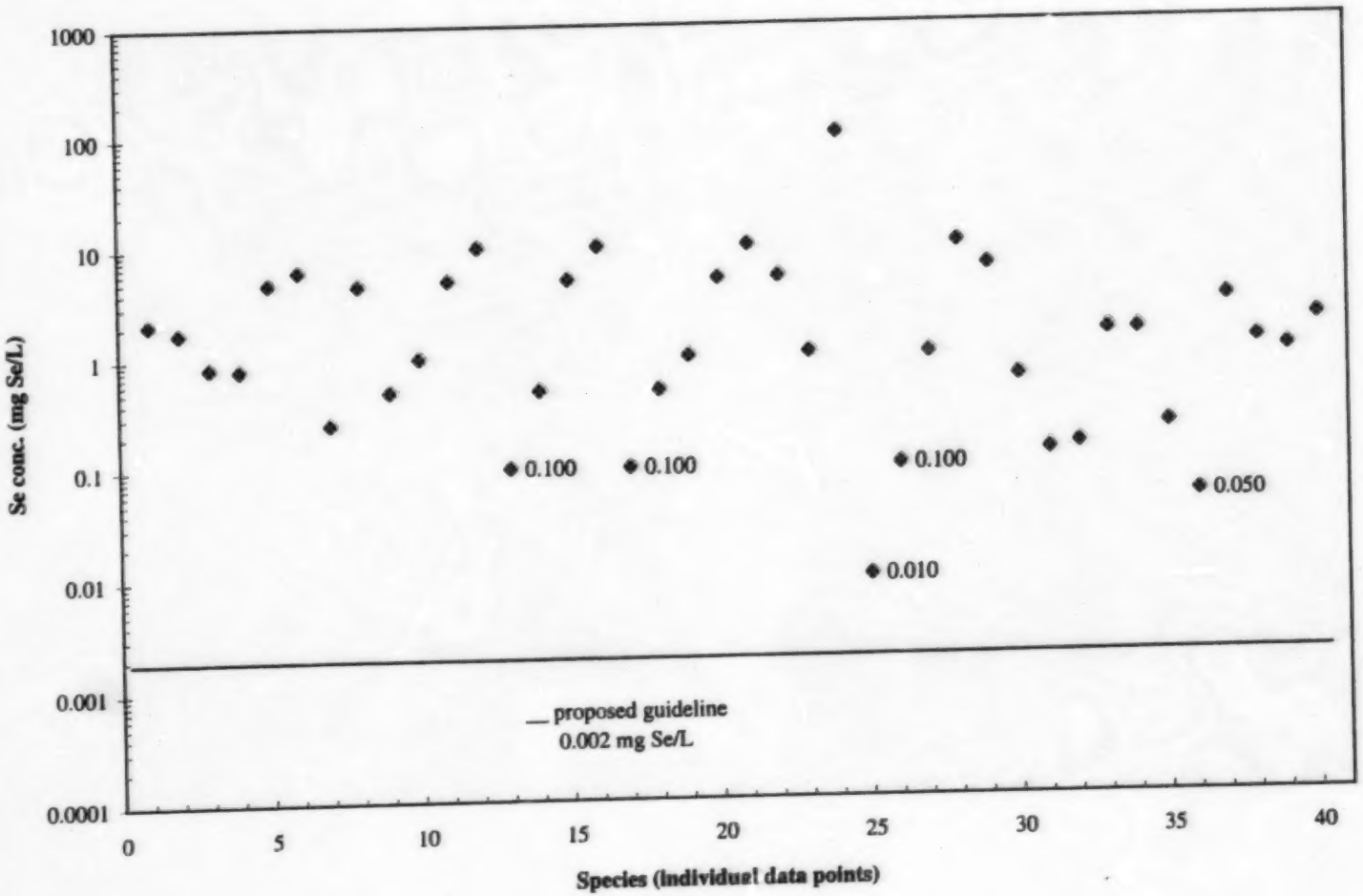

Figure 9.23: Se toxicity to different species of marine invertebrates

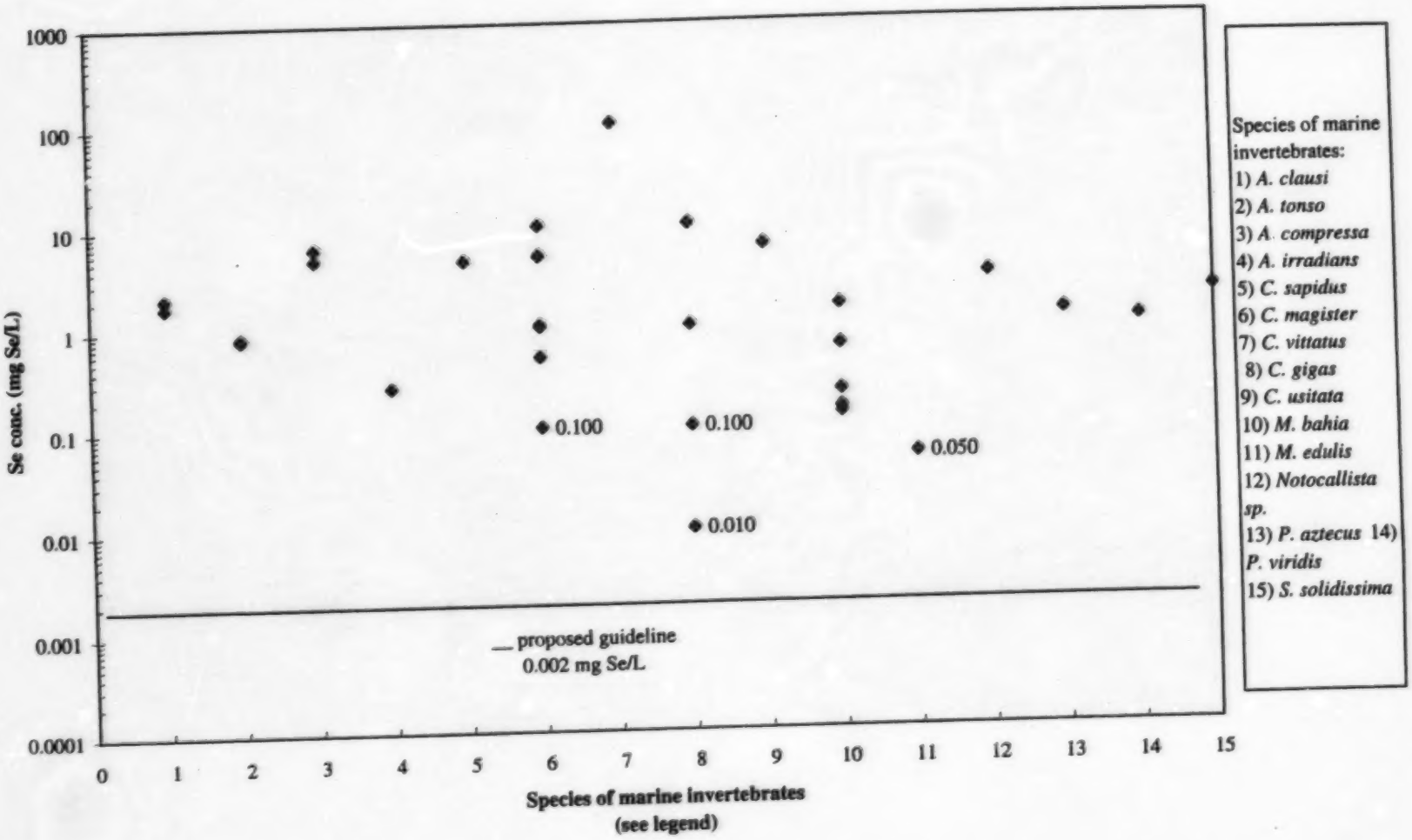

Figure 9.24: Se toxicity (96-h LC_{50}) to marine invertebrates

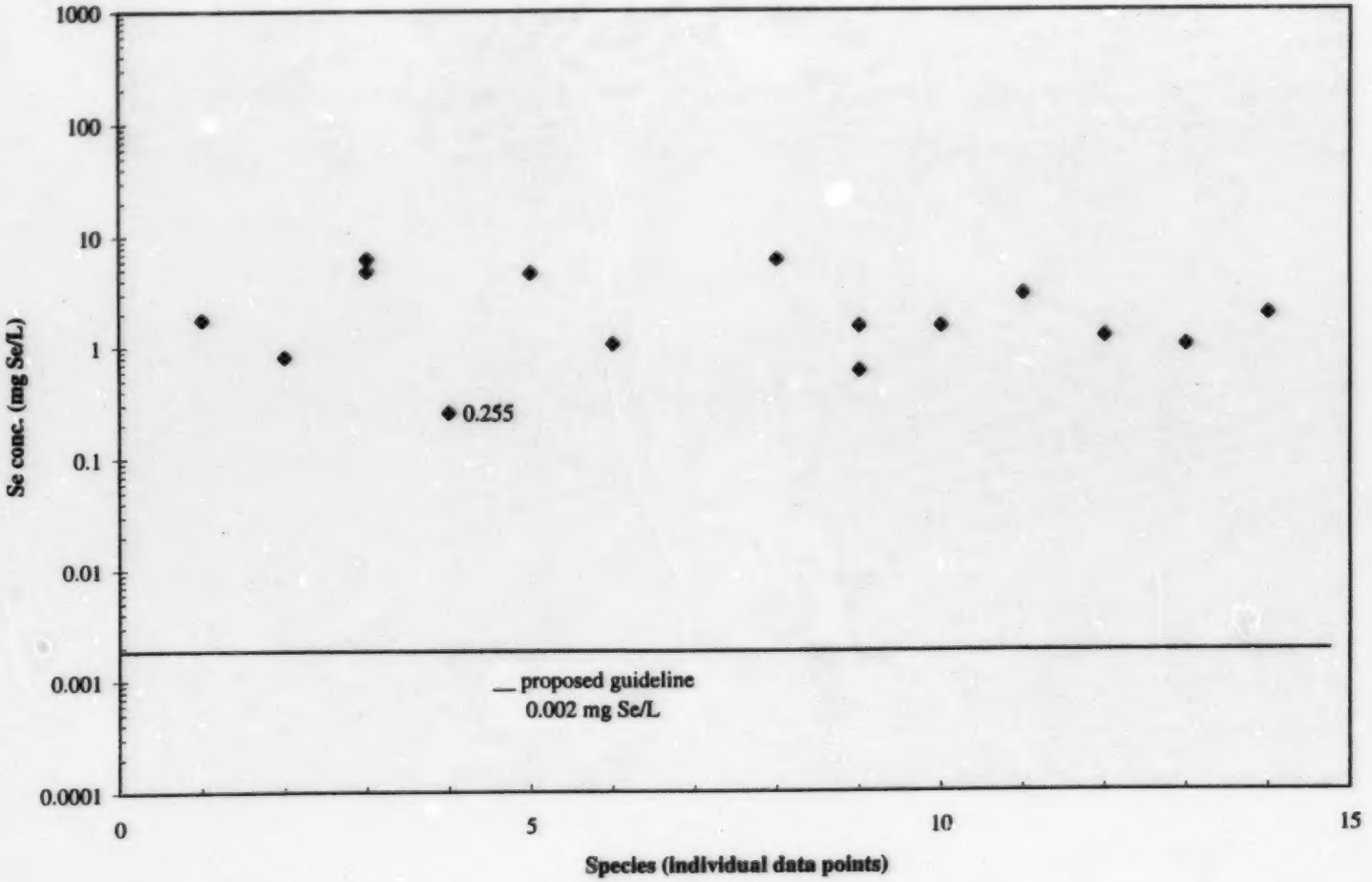

Figure 9.25: Se toxicity to marine algae and macrophytes

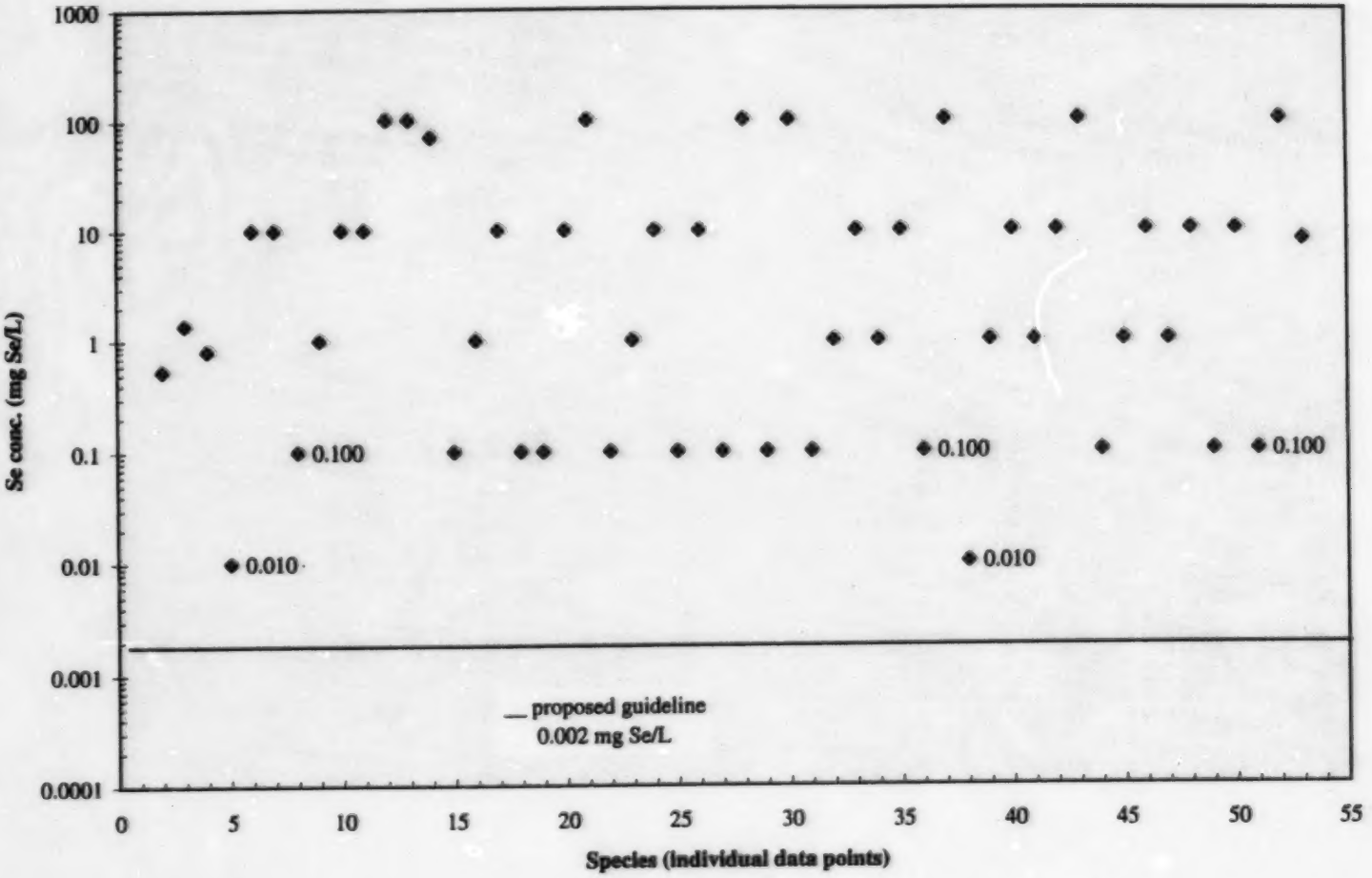

Figure 9.26: Se toxicity to different species of marine algae and macrophytes

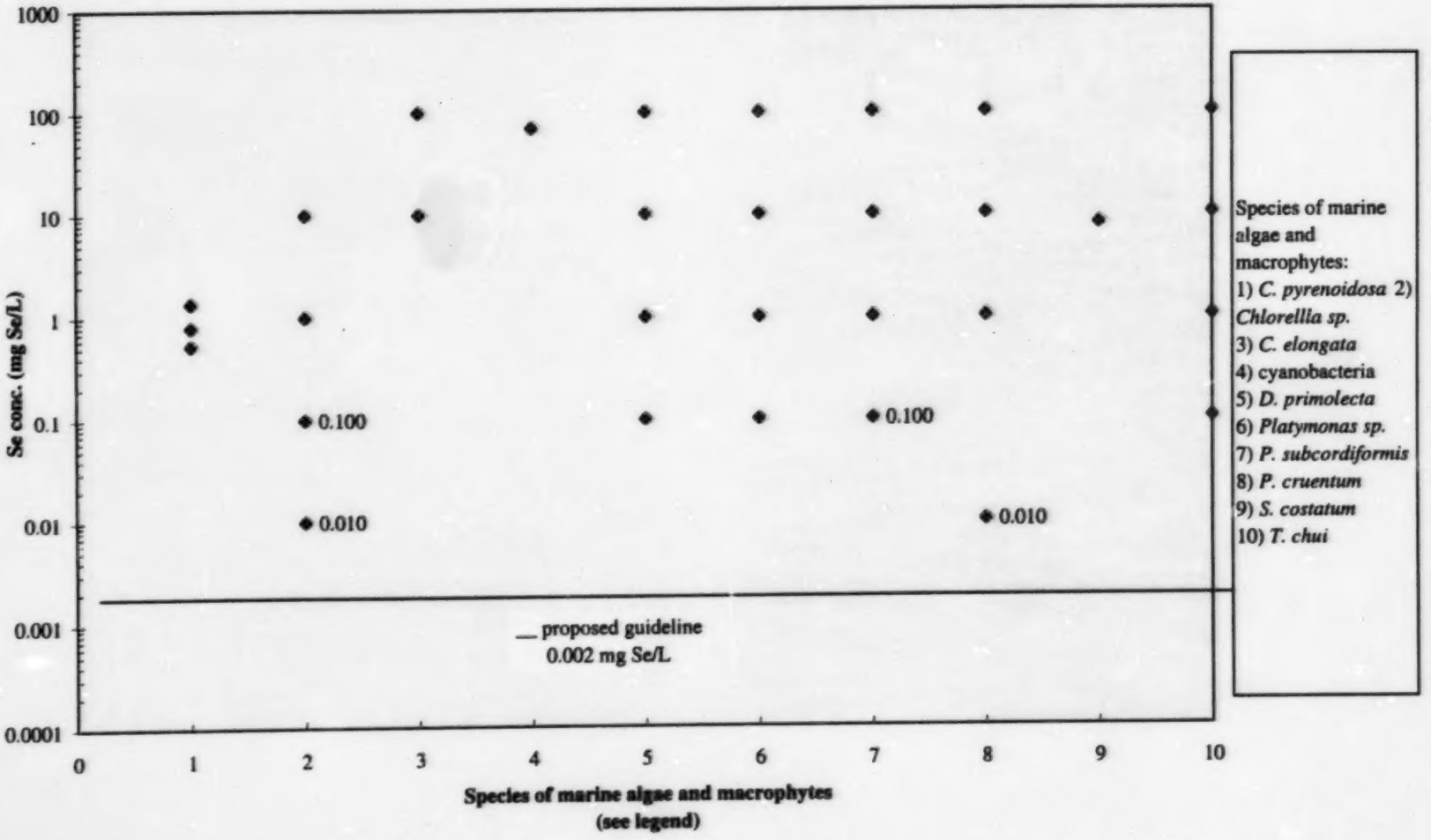
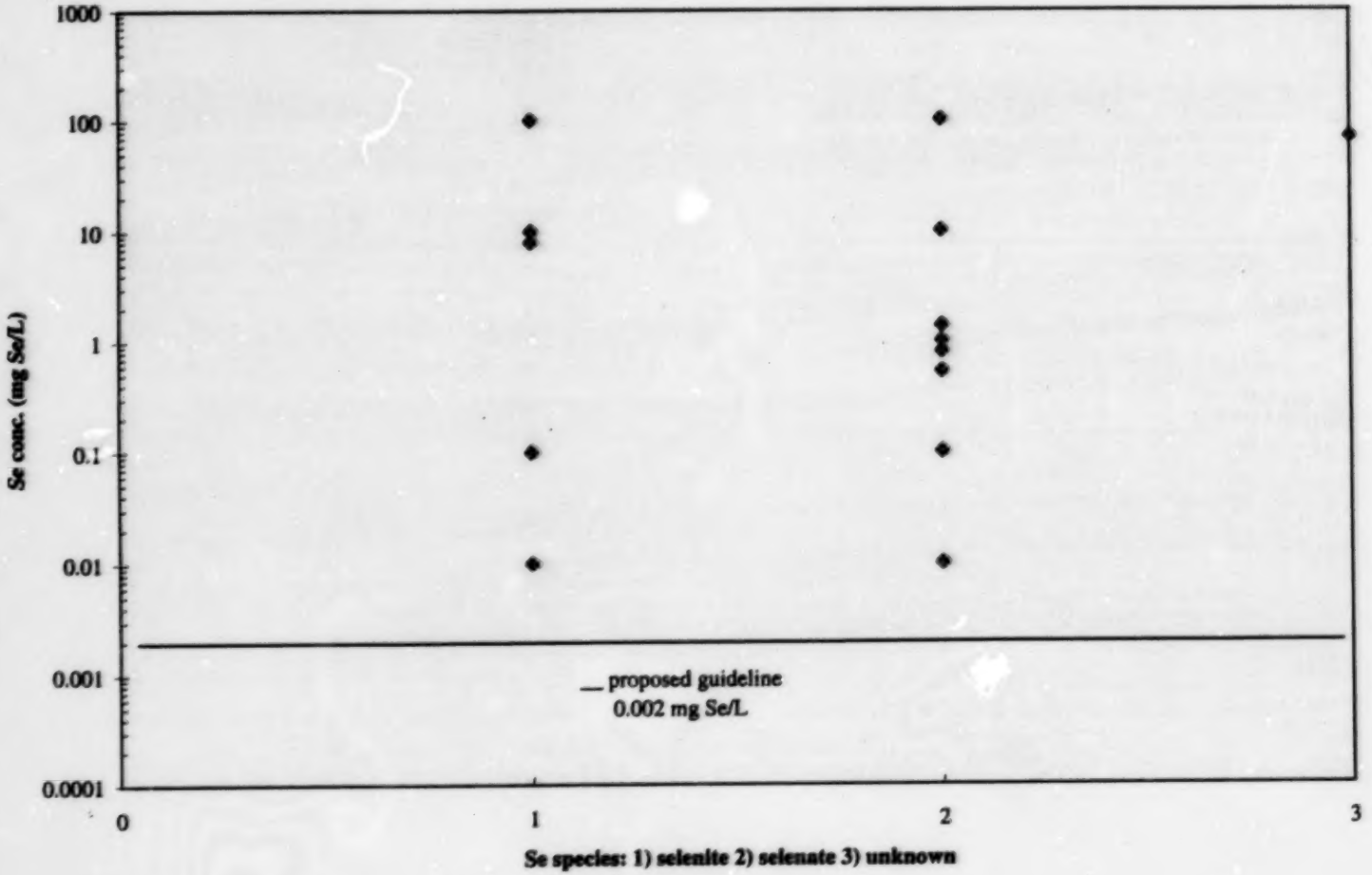
Figure 9.27: Se toxicity to marine algae and macrophytes vs Se species